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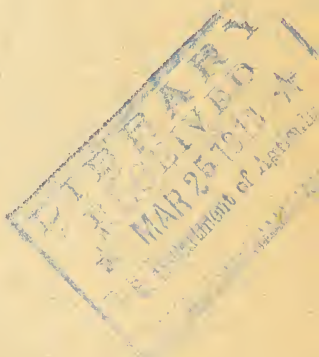
Issued March 25, 1913.

U. S. DEPARTMENT OF AGRICULTURE,
BUREAU OF SOILS—BULLETIN NO. 91.
MILTON WHITNEY, CHIEF.

THE MICROSCOPIC DETERMINATION OF SOIL-FORMING MINERALS.

BY

W. J. McCAUGHEY AND WILLIAM H. FRY,
Scientists in Chemical and Physical Laboratories.



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LETTER OF TRANSMITTAL.

U. S. Department of Agriculture,
Bureau of Soils,
Washington, D. C., October 14, 1912.

Sir: I have the honor to transmit the manuscript of an article entitled The Microscopic Examination of Soil-Forming Minerals, by W. J. McCaughey and William H. Fry, Scientists in the Chemical and Physical Laboratories of the Bureau of Soils. This article discusses the methods of mineralogical research as applied to the study of soils and embodies the results of work along this line in the Bureau laboratories. I believe the information given will be of interest to students of the soil and therefore recommend that the material be published as Bulletin No. 91, of this Bureau.

Very truly, yours,

Milton Whitney,
Chief of Bureau.

Hon. James Wilson,
Secretary of Agriculture.

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THE MICROSCOPIC DETERMINATION OF SOIL-FORMING MINERALS.

INTRODUCTION.

Soils are largely the result of certain natural processes, physical, chemical, and biological, upon rock and rock materials. Consequently the greater part of the soil is made up of mineral fragments coming from the original rock components and to some extent of decomposition and alteration products derived from the degradation products.[1] It is obvious that to understand the properties of a soil, and especially those properties which are dependent upon origin, mode of formation, and composition, the minerals of the soil must be known. Much attention has been given the mechanical composition of the soil and its consequent physical properties; the chemical composition, organic as well as inorganic; and the biological composition, especially in recent years. But little attention has been given the mineralogical composition, and that in spite of the great advances in mineralogical technique, especially along optical lines incident to rapid development of petrographical and geological investigations.

The application to soil problems of the methods developed for petrographical work involves some serious difficulties. Soil aggregates do not lend themselves readily to microscopic examination as do thin rock sections. Thin sections of soils require preliminary embedding, and no medium has been found which is entirely satisfactory. Soil particles are very often coated with ferruginous or other material which must be removed before they can be examined satisfactorily. Generally it is desirable to examine the entire mineral taken from the soil rather than a section of it, and finally the mineral grains which are of most interest are those approaching the silt and clay dimensions.

The present bulletin has been prepared to bring together and describe those methods which have been found useful in the laboratory of this Bureau. In no sense is it proposed as a textbook or exhaustive treatise, and the student is referred to the standard authorities, of whose publications free use has been made here, including

[1] See Merrill, Rocks, Rock Weathering, and Soils; Cameron and Bell, Bul. No. 30, Bureau of Soils, U. S. Dept. Agriculture; Cameron, Jour. Phys. Chem., 14, 320 and 393 (1910); and The Soil Solution, Easton, Pa., 1911.

Rosenbusch, Iddings, Johannsen, Winchell, and especially Dana. Nowhere, however, have the methods been brought together in a form which makes them readily available to the soil investigator, and in trying to meet this want it has been deemed desirable to give the theoretical grounds for these methods. For this reason the treatment is to some extent didactic, not because it is intended as a teacher's textbook, but because it is intended as a manual or handbook for the laboratory worker in scanning soils.

PREPARATION OF SAMPLES.

Before any satisfactory mineralogical examination of a soil can be made the sample must be subjected to a preliminary treatment. The technique in examining particles of a diameter of 1 or 2 mm. varies considerably, at least in detail, from that required for the examination of particles less than 0.05 mm. Frequently the soil particles are in aggregates containing various minerals which must be separated. Again, the minerals, as stated, are often disguised by a coating of ferruginous or other like materials. Various methods are available for the preparation of the material, and of these the methods which have proved most valuable will be described in the following paragraphs.

ASSORTING THE PARTICLES ACCORDING TO SIZE.

This method is in all essential features the well-known mechanical analysis of soils as employed in this Bureau.[1] To remove the adhering ferruginous and clayey material the sample of soil is shaken for some hours in a bottle with a dilute (about 0.3 per cent) solution of ammonia. The ferruginous and organic coating on the particles is thus shaken off and deflocculated. On standing for a short while most of the particles with a diameter greater than 0.05 mm. will settle to the bottom of the bottle and the finer particles can be decanted with the supernatant liquid. Further sedimentation from the supernatant liquid can be effected by long standing or quickly with a centrifuge, and it is customary to separate thus the silt (particles with a diameter of 0.05 to 0.005 mm.) from the clay (particles with a diameter less than 0.005 mm.). The clay is recovered by evaporation of a considerable volume of wash water and contains generally most of the ferruginous material originally coating the soil particles and always more or less organic matter, which tends to bind or "cake" the dried residue. For this reason, as well as the very small size of the particles, clay does not lend itself readily to mineralogical methods and is but seldom examined. The sands are separated by sifting through sieves with appropriate sized meshes. This

[1] Bul. No. 24, Bureau of Soils, U. S. Dept. of Agr. The Centrifugal Method of Mechanical Soil Analysis, by Lyman J. Briggs, F. O. Martin, and J. R. Pearce.

process of sifting is sometimes repeated with all of the separates coarser than clay to complete the separations and break up the aggregates of silt which are apt to form in many cases. When the coating of ferruginous material is unusually persistent, it is sometimes necessary to wash the separate further with dilute hydrochloric acid.

Certain generalities have been established regarding the composition of these "mechanical separates" of a soil.[1] Quartz predominates in the coarser separates, while as the diameter decreases there is present in increasing proportions fragments of the softer minerals and those possessing good cleavage, such as kaolinite, the feldspars, etc. It is probable from a priori considerations and from chemical analyses that the clay separate is richest in such minerals, but this can not now be definitely proved. On the other hand, ferric hydroxide, alumina, and kaolin also tend to accumulate in the clay. The separates, after being sifted and washed, are dried, and may be conveniently kept in vials until needed.

For mineralogical purposes it is usually convenient to separate the soil into four portions, viz:

	Diameter. Mm.
Clay (less than)	0.005
Silt	0.005— .05
Fine sand	.05— .1
Sands, gravel, etc. (above)	.1

The separates should usually be examined first with a view of recognizing the presence of some characteristic or unusual component. Often a particular mineral can be removed by picking it off the microscope slide with a moistened pin point or similar instrument and subjected to a special mineralogical or microchemical examination and data secured which would otherwise be lost. Magnetite can conveniently be separated in this preliminary examination by a magnetized knife blade, and other procedures which will furnish preliminary information useful as a guide to further work will often suggest themselves.

FURTHER SEPARATION BY MEANS OF HEAVY SOLUTIONS.

To facilitate the examination it is sometimes advisable to assort the sands into three separates by the use of heavy solutions. The solutions generally used will be described presently when discussing the specific gravity of the minerals. By such means the very abundant quartz is eliminated at the start, permitting a more ready examination of the other minerals and in addition furnishing some idea of their relative specific gravities. This separation is best accomplished in a tube with a side neck, as in figure 1. The sand is

[1] See in this connection Bul. No. 54, Bureau of Soils, U. S. Dept. of Agr.

placed in the wide tube, the heavy liquid poured in, stoppers inserted, and the tube and its contents shaken. The tube is permitted to stand for a few hours or overnight. The stoppers are removed, and the heavy liquid poured in at *B*, which floats off the lighter fraction at *A* into an awaiting beaker. In order to facilitate the separation it is advisable to stir the fraction at *A* with a glass rod and then the rising liquid carries it off. The heavier sediment *C* is brought on a filter paper and washed. With the silts it is necessary to use the centrifuge to overcome the effect of surface action, since otherwise the silts may either rise or sink in the tube. For this reason, when working with the silts, a tube of the design shown in figure 2 is used, so made that it fits into the centrifuge tubes used in mechanical analysis. The effect produced by the rapid rotation is soon evidenced and a separation of the silt particles according to their specific gravities is readily made. A simple centrifuge may be easily constructed of an iron washer into which a tube fits and is caught by a flange. The washer is provided with two holes on opposite sides. Into these holes iron wires are fitted and carried thence to a ring support. The wires are about 2 to 3 feet long. The ring support furnishes a hand grip for swinging the apparatus by hand.

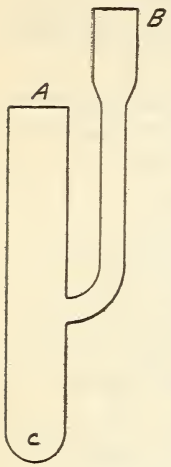


FIG. 1.—Tube for separation of soil grains by means of heavy solutions.

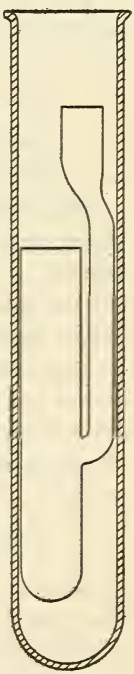


FIG. 2.—Tube, same as fig. 1, prepared for centrifuge.

More cheaply, but less satisfactorily, a test tube may be used for separating the minerals with the aid of heavy solutions. After shaking the grains in a tube with a heavy liquid they are permitted to settle overnight. The end of a pipette is immersed beneath the lighter fraction and the contents of pipette permitted to escape, floating the lighter part into an awaiting beaker.

The Harada separator (fig. 3) may be used to separate the lighter from the heavier constituents. The lower stopcock is closed and a solution of the required density poured in, and the soil particles introduced. The whole is shaken and allowed to stand until the heavier particles have sunk and the lighter ones are floating on the surface. Thus the heavier particles are below the upper stopcock and the lighter ones above. The upper cock is then closed. Since the heavier particles carry down some of the lighter, and the lighter buoy up some of the heavier, it is well to shake the separator again and to place it upside down. This tends further to separate the particles. The vessel is then slowly tilted and the upper cock opened. In this way the heavy

and light material pass each other. When this is complete the upper cock is closed and the heavier material drawn off from the bottom and the lighter from the top.

PRELIMINARY EXAMINATION.

The physical properties of the individual soil grains are of great importance, since the determination of the nature and magnitude of these various properties makes it possible to separate the minerals and to identify them. The physical properties of minerals fall naturally into two groups, either dependent upon the chemical composition of the minerals or upon their crystallographic and optical characteristics.

Properties dependent upon chemical composition of the minerals are the specific gravity and the behavior of the minerals in a magnetic field. Both of these properties are entirely distinct from their crystal form and are of especial importance in the mechanical separation of soil minerals.

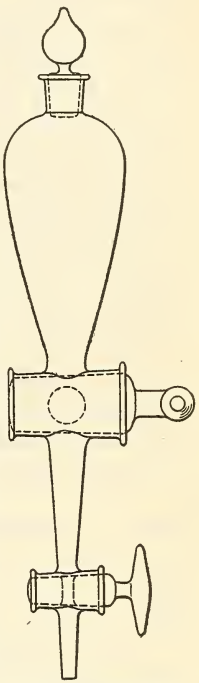


FIG. 3.—The Harada separator.

SPECIFIC GRAVITY.

Each mineral on account of its definite chemical composition possesses a specific gravity which is more or less constant and characteristic. Owing to impurities, inclusions, or sometimes to other causes of an adventitious nature, there is a certain range of variation to be expected in any given mineral. But this range is usually within quite narrow limits. The importance of specific gravity in soil mineralogy lies chiefly in that it permits of the separation of heavy from light minerals. In the determination of soil minerals it has been found practicable to separate the sands, on account of the predominance of quartz, into three fractions: (1) Minerals lighter than quartz, with specific gravity below 2.63; (2) quartz and minerals with specific gravity between 2.63 and 2.68; (3) minerals heavier than quartz, specific gravity above 2.68. The separation into these grades is usually accomplished by the use of heavy solutions or liquids with high specific gravity, following one of the procedures just described. There are but few liquids suited for this purpose. They should possess the three essentials—high gravity, low viscosity, and low coefficient of expansion. In general, inorganic salts in water yield solutions which on account of their high viscosity are not so well adapted to separating mineral grains as are the organic liquids. It takes much longer for the grains to settle, and in the finer grains the surface effect working against separation is of higher magnitude than in the organic liquids.

Thoulet's solution consists of mercury iodide and potassium iodide in proportion 1.24 to 1, dissolved in water. It has a maximum density of 3.19, and may be diluted at will with water. This solution is very poisonous and has a strong corrosive influence upon the skin.

Klein's solution is cadmium borotungstate in water. It has a maximum density of 3.3, may be diluted with water, and is not poisonous or corrosive, but is very sticky and has a rather high viscosity.

Methylene iodide, with a maximum density of 3.3, may be diluted with benzine.

Acetylene tetrabromide, with a maximum density of 3.0, may be diluted with benzine.

Rohrbach's solution, a solution of barium mercuric iodide, has a maximum density of 3.6, but undergoes decomposition upon dilution.

The determination of the specific gravity of a soil grain is conveniently made by using a series of vials containing solutions of graduated densities. By trial a solution is found in which the grain just floats and another solution in which it just sinks, and by interpolation the specific gravity of the mineral is determined. This determination, however, can only be satisfactorily made with grains of appreciable size. In soil mineralogy the finest sand grains are the smallest whose gravity can be so determined. Again, it is only of service with mineral grains of unquestioned purity, without incrusting layers of alteration products. Specific gravities of the principal soil minerals are given in Table I.

TABLE I.—*Arrangement of soil-forming minerals according to their specific gravities.*

Specific gravity.	Mineral.	Specific gravity.	Mineral.	Specific gravity.	Mineral.	Specific gravity.	Mineral.
2.1	Graphite.	2.70	Schiller spar.	3.10	Tourmaline.	3.50	Grossularite.
2.1	Chabazite.	2.70	Labradorite.	3.10	Glaucophane.	3.56	Topaz.
2.16	Stilbite.	2.72	Calcite.	3.16	Apatite.	3.60	Cyanite.
2.17	Hyalite.	2.73	Bytownite.	3.18	Fluorite.	3.60	Spinel.
2.19	Analcite.	2.72	Penninite.	3.19	Bronzite.	3.68	Limonite.
2.21	Opal.	2.72	Clinochlore.	3.20	Enstatite.	3.75	Pyrope.
2.23	Natrolite.	2.72	Scapolite (wernerite).	3.20	Andalusite.	3.74	Staurolite.
2.28	Sodalite.			3.22	Hornblende.	3.90	Almandite.
2.31	Gypsum.	2.72	Beryl.	3.22	Smaragdite.	3.94	Siderite.
2.31	Nosean.	2.73	Meionite.	3.22	Uralite.	3.60	Ceylonite.
2.31	Scolecite.	2.74	Talc.	3.22	Sillimanite.	3.90	Octahedrite.
2.31	Tridymite.	2.76	Anorthite.	3.26	Chloritoid.	3.94	Hercynite.
2.45	Hauynite.	2.78	Chlorite (ripidolite).	3.30	Diopside.	3.95	Corundum.
2.47	Leucite.			3.30	Diallage.	4.06	Perovskite.
2.50	Basic glasses.	2.78	Pinite.	3.30	Omphacite.	4.08	Picotite.
2.56	Nephelin.	2.78	Phlogopite.	3.35	Zoisite.	4.00	Brookite.
2.56	Microcline.	2.85	Muscovite.	3.39	Hypersthene.	4.15	Melanite.
2.56	Orthoclase.	2.86	Wollastonite.	3.39	Augite.	4.25	Rutile.
2.56	Sanidine.	2.90	Dolomite.	3.39	Epidote.	4.45	Barite.
2.60	Iolite.	2.90	Melilite.	3.39	Allanite.	4.68	Zircon.
2.60	Serpentine.	2.94	Aragonite.	3.41	Olivine.	4.46	Chromite.
2.63	Albite.	3.01	Biotite.	3.43	Vesuvianite.	4.75	Ilmenite.
2.65	Oligoclase.	3.01	Actinolite.	3.45	Arfvedsonite.	5.20	Magnetite.
2.65	Quartz.	3.01	Magnesite.	3.48	Titanite.	5.30	Hematite.
2.68	Andesine.	3.01	Tremolite.	3.49	Acmite.	6.65	Cassiterite.

MAGNETISM.

There is one mineral commonly occurring in soils which is readily attracted by an ordinary bar magnet, which property distinguishes it from several others of different chemical composition but of similar appearance. This mineral is magnetite, which is similar in physical appearance to chromite, ilmenite, allanite, etc. By the use of a bar or horseshoe magnet or magnetized pocketknife, magnetite is readily separated from other minerals.[1] To detect weak magnetism in minerals, or polarity, use is made of a compass needle.

Early in the study of magnetism it was found by Michael Faraday that not only iron was magnetic, but that its salts and even solutions of its salts were attracted by an electromagnet. With the use of a strong electromagnet all the iron-containing minerals can be separated from the nonferruginous ones, even when the percentage of iron in the mineral is quite small. By varying the intensity of the magnetic field the iron minerals themselves may be separated into several groups. This variation in intensity of the electromagnetic field may be obtained by using adjustable poles, which may be brought together and separated at will. It is better in practice, however, to employ a lamp resistance which will control the current and produce a definite field intensity, leaving the poles at a certain fixed distance apart.

Doelter has given special attention to the electromagnetic separation of the iron-containing minerals and some others, and arranges them into 12 groups, as shown in Table II.

TABLE II.—*Doelter's list of electromagnetic minerals.*

Group.	Mineral.	Group.	Mineral.
1	Magnetite.	7	Tourmaline, bronzite, vesuvianite.
2	Hematite, ilmenite.	8	Staurolite, actinolite.
3	Chromite, siderite, almandite.	9	Olivene, pyrite, chalcopyrite, vivianite, $FeSO_4$.
4	Ilvaite, hedenbergite, ankerite, limonite.		
5	Iron-rich augite, pleonaste, arfvedsonite.	10	Biotite, chlorite, rutile.
6	Hornblende, light-colored augite, epidote, pyrope.	11	Hauynite, diopside, muscovite.
		12	Nepheline, leucite, dolomite.

CRYSTAL FORM AND CLEAVAGE.

In soil mineralogy crystal form is of comparatively little importance, since the minerals seldom occur with crystal terminations, owing to the mechanical forces to which they have been subjected and the consequent rounding of the edges and faces. There are some excep-

[1] Pyrrhotite is sometimes magnetic and attracted by the magnet, but its occurrence in soils is far less common.

tions, notably zircon and rutile, which occur often with terminations and faces. This is due to the facts that zircon and rutile always occur in well-defined crystals, that they have superior hardness, and that they offer unusual resistance to chemical alteration. In soils derived from limestones, invariably some quartz occurs in well-defined crystals. Minerals included in a host also show crystal form, as in so-called microlites.

Cleavage brings about certain structural relations in the mineral fragments. The micas, on account of their strongly developed cleavage, always appear in flat plates of even thickness, and without definite outline. Minerals with a prismatic cleavage, such as amphiboles, pyroxenes, etc., form elongated fragments which show extinction in polarized light at definite angles to the axis of elongation. These elongated forms may still further be distinguished by the optical nature of the elongation. The feldspars with a perfect side pinacoid cleavage and basal pinacoid yield tabular-shaped forms; sometimes elongated forms with parallel sides; sometimes flat tabular fragments. Minerals like quartz, which possess little cleavage, appear in irregular shapes. The characteristic appearance of soil grains due to cleavage relations are given in Table III.

TABLE III.—*Soil-forming minerals arranged according to their form and structure relations.*[1]

A. Tables and plates with corresponding parallel cleavage			Goethite. Pyrrhotite. Hematite. Biotite. Phlogopite. Sericite. Paragonite. Brookite. Muscovite. Chlorite. Penninite. Clinochlore. Chloritoid. Kaolin. Tridymite. Stilbite.
B. Flattish formed particles without corresponding basal (parallel) cleavage (in crossed nicols), thus not giving high polarization at all places.	1. Opaque to translucent		Graphite. Hematite. Ilmenite. Glauconite.
	2. Transparent	*a.* Isometric and amorphous	Opal. Nosean.
		b. Hexagonal	Quartz.
		c. Tetragonal	Meionite.
		d. Orthorhombic	Olivine. Barite.
		e. Monoclinic	Orthoclase. Sanidine. Gypsum. Schiller spar.
		f. Triclinic	Plagioclase. Microcline.

[1] Adapted from Steinriede.

- C. Elongated forms (crystals and cleavage pieces).
  - 1. Opaque to translucent.
    - Ilmenite.
    - Goethite.
    - Rutile.
    - Limonite (feathery).
  - 2. Transparent.
    - *a*. Optically uniaxial.
      - Wernerite.
      - Zircon.
      - Rutile.
      - Tourmaline.
      - Nepheline.
      - Apatite (as microlith).
      - Calcite, Dolomite — Rarely elongated.
    - *b*. Optically biaxial.
      - Straight extinction in direction of cleavage.
        - Sillimanite.
        - Staurolite.
        - Enstatite.
        - Bronzite.
        - Hypersthene.
        - Allanite.
        - Andalusite.
        - Zoisite.
        - Aragonite.
        - Wollastonite.
        - Epidote.
        - Natrolite.
      - Oblique extinction from the direction of the length.
        - Orthoclase.
        - Sanidine.
        - Augite.
        - Diopside.
        - Diallage.
        - Acmite.
        - Gypsum.
        - Scolecite.
        - Hornblende.
        - Actinolite.
        - Smaragdite.
        - Tremolite.
        - Glaucophane.
        - Uralite.
        - Cyanite.

- D. Crystals, grains, splinters, etc., without corresponding extent of surface or extension in length.
  - 1. Opaque to translucent.
    - Magnetite (grains and octahedra).
    - Ilmenite.
    - Pyrite and marcasite.
    - Pyrrhotite.
    - Octahedrite.
    - Rutile.
    - Garnets.
    - Spinel.
    - Chromite.
  - 2. Transparent.
    - *a*. Amorphous opal.
    - *b*. Isometric.
      - Garnets: Almandite, Pyrope.
      - Sodalite.
      - Hauynite.
      - Nosean.
      - Analcite.
      - Fluorite.
      - Perovskite.
    - *c*. Optically uniaxial.
      - Hexagonal.
        - Calcite.
        - Dolomite (rarely elongated).
        - Corundum.
        - Siderite.
        - Eleolite.
        - Nepheline.
        - Apatite.
        - Quartz.
      - Tetragonal.
        - Rutile.
        - Zircon.
        - Octahedrite.
        - Meionite.
        - Wernerite.
        - Melilite.
        - Vesuvianite.
    - *d*. Optically biaxial.
      - Orthorhombic.
        - Olivine.
        - Staurolite.
        - Andalusite.
        - Zoisite.
        - Barite.
        - Iolite.
      - Monoclinic.
        - Orthoclase, Sanadine, Augite — Rarely in grains.
        - Omphacite.
        - Salite.
      - Triclinic.
        - Cyanite.
        - Microcline.
        - Plagioclase: Albite, Oligoclase, Labradorite, Anorthite.

HARDNESS.

The hardness of the minute mineral grains occurring in a soil has little diagnostic value. At times, however, it makes possible the distinction of one mineral from another whose appearance is quite similar. The hardness of the various minerals, however, has an important relation to their occurrence in the mechanical soil separates. In the attrition, by natural mechanical forces and those of tillage and intermovements of the soil grains,[1] the softer minerals are ground finer than those of superior hardness. Consequently the minerals less fitted to withstand attrition are found in the silts and clays.

The hardness of grains may be tested between two glass slides of known hardness, or the grains may be mounted on a piece of lead or end of a pencil by the use of a little pressure and the hardness tested on an arbitrary scale, such as Mohr's. In general, the secondary minerals formed by weathering are less hard than the original minerals composing the rock. A list of the soil-forming minerals arranged according to their hardness is given in Table IV.

TABLE IV.—*Soil-forming minerals arranged according to hardness.*

Hardness.	Mineral.	Hardness.	Mineral.	Hardness.	Mineral.	Hardness.	Mineral.
1.0	Talc.	3.75	Strontianite.	5.5	Limonite.	6.5	Zoisite.
1.5	Steatite.	3.75	Witherite.	5.5	Perovskite.	6.5	Chondrodite.
1.5	Pyrophyllite.	4.0	Aragonite.	5.7	Cyanite.	6.5	Augite.
2.0	Kaolin.	4.0	Fluorite.	5.5	Wernerite.	6.5	Rutile.
2.0	Gypsum.	4.0	Dolomite.	5.5	Titanite.	6.5	Sillimanite.
2.0	Vivianite.	4.0	Siderite.	5.75	Diopside.	6.75	Obsidian.
2.5	Biotite.	4.25	Phillipsite.	5.75	Leucite.	7.0	Quartz.
2.5	Chlorite.	4.5	Wollastonite.	5.75	Tremolite.	7.0	Garnet.
2.5	Muscovite.	4.5	Chabazite.	6.0	Hypersthene.	7.0	Axinite.
2.75	Phlogopite.	4.75	Apophyllite.	6.0	Nepheline.	7.0	Tourmaline.
3.0	Calcite.	5.0	Apatite.	6.0	Orthoclase.	7.5	Cordierite.
3.0	Anhydrite.	5.25	Natrolite.	6.0	Microcline.	7.5	Andalusite.
3.0	Celestite.	5.5	Enstatite.	6.0	Albite.	7.5	Staurolite.
3.0	Barite.	5.5	Hauynite.	6.0	Labradorite.	7.5	Beryl.
3.25	Wavellite.	5.5	Datolite.	6.0	Anorthite.	7.5	Zircon.
3.5	Serpentine.	5.5	Opal.	6.5	Spodumene.	8.0	Spinel.
3.5	Laumontite.	5.5	Analcite.	6.5	Chloritoid.	8.0	Topaz.
3.75	Heulandite.	5.5	Nosean.	6.5	Prehnite.	9.0	Corundum.
3.75	Stilbite.	5.5	Sodalite.	6.5	Epidote.	10.0	Diamond.

INCLUSIONS.

The occurrence of microscopic inclusions has a certain diagnostic value in the determination of minerals. The occurrence of microlites in certain minerals has characteristic bearing on and sometimes reveals the processes through which the mineral has been produced. These inclusions are manifestly dependent upon the conditions prevailing when the mineral was formed. They are generally of three types: (1) Gaseous or liquid, (2) glassy, or (3) other minerals.

[1] See Cameron, The Soil Solution, Easton, Pa., 1911, p. 194 et seq.

Primary quartz from igneous rocks has minute inclusions of gas and liquid which are distinctive. Apatite, rutile, zircon, and sillimanite frequently occur as microlites in other minerals. These inclusions are frequently not only characteristic of certain minerals but even of definite rock provinces and of definite conditions of metamorphism, so that the determination of microscopic inclusions furnishes a means of determining the source of the soil grains. Inclusions are thus often a clue to the original rock from which at least part of the soil was derived, and show the original condition of the grain itself, whether primary or secondary.

MICROCHEMICAL REACTIONS.

In the earlier studies of rocks, before petrological methods had reached their present efficiency, certain useful microchemical reactions were perfected, notably by Boricky. These microchemical reactions are useful at times in distinguishing soil minerals whose optical properties are very similar. When hydrofluosilicic acid acts upon a silicate, the latter is slowly decomposed, and the bases form fluosilicates which possess characteristic crystal habits. For instance, potash forms little cubes or tables much like halite crystals. Soda forms hexagonal prisms, often terminated with pyramids. Calcium forms characteristic crystals resembling somewhat an elongated barrel. Magnesia and alumina also form characteristic crystals. It is possible with hydrofluosilicic acid to perform a careful qualitative analysis upon a minute grain. The testing is done on an object glass varnished for protection with Canada balsam. The object lens of the microscope is protected by cementing a cover glass to its extremity with a drop of glycerin. Other valuable microchemical tests are the cæsium-alum test for alumina, where large octahedrons are obtained by adding cæsium chloride and sulphuric acid to the solution of the mineral. This is an important method for distinguishing, chemically, certain minerals, notably the orthorhombic from the monoclinic pyroxenes.

The gypsum test for calcium is important and characteristic. From dilute sulphuric acid solution calcium separates as gypsum either in monoclinic prisms, often needle-like and showing inclined extinction, or as twins. Certain silicates, as nepheline and the minerals associated with it in alkali rocks, as sodalite, hauynite, noselite, etc., also some zeolites, olivine, chlorite, etc., are soluble in hydrochloric acid with the separation of gelatinous silica. These minerals may be distinguished from others of similar physical properties but not soluble in hydrochloric acid by placing the grain upon an object glass, adding a drop of hydrochloric acid, and evaporating to dryness in a desiccator. The gelatinous silica may then be stained with a solution of some organic dye, as fuchsin, which makes

the siliceous gel readily visible under the microscope. Many other microchemical tests are occasionally of value, but those just cited are the more useful ones in soil mineralogical investigations. For a fuller discussion of the subject the special texts should be consulted.[1]

THE MICROSCOPE.

For mineralogical soil investigations the first essential in equipment must be a microscope. The microscopes which are particularly arranged for petrographic work are the most desirable. Such a microscope is, however, expensive and is not necessary if one possesses an ordinary microscope of sufficient quality which can be modified for mineralogical work. Such a microscope should have—

(1) A rotating stage provided with a centering device. The rotating stage is essential in the determination of extinction angles. The centering device is necessary in the obtaining of interference figures in observation in convergent polarized light. It is desirable that the rotating stage be graduated into degrees.

(2) A $\frac{1}{2}$-inch and a $\frac{1}{8}$-inch objective.

(3) A condensing system in the substage. For observation with convergent polarized light it is desirable that the microscope be fitted with a fine micrometer adjustment in order to measure the thickness of the soil grain, in the determination of birefringences.

To adapt such a microscope for mineralogical study it is necessary to equip it with two nicols, a polarizer, and an analyzer. These can be obtained from dealers in optical goods and can be readily fitted to the microscope. The polarizer is mounted in the substage below the condensing lens, and is so fitted that it may be rotated. The manufacturers commonly provide analyzers that screw in the objective and then on the body tube of the microscope. This form, however, is not desirable on account of the difficulty in removing it and because of the lack of a slit for the introduction of a selenite plate. The cap form of nicol is preferable, as it can easily be fitted over the eyepiece of the microscope. In the cap nicol at the 45° position a slit is provided for the insertion of a selenite plate or a quartz wedge, which are used in the determination of the optical nature of the mineral and its elongation.

It is also desirable that the eyepiece should be provided with two cross hairs arranged at right angles to each other. The nicols should be so adjusted that the cross hairs mark the vibration direction of the nicols when they are crossed. The vibration direction of the polarizer may be determined by viewing powdered tourmaline under the microscope in light that is transmitted through the polarizer.[2] The tourmaline should be immersed in oil or water to obviate the

[1] See, for instance, Behrens' Mikrochemischen Analyse, 1895. English edition, translated by Judd.

[2] Rubellite will not do, as there is no appreciable absorption in this variety of tourmaline.

dark edges of the grains observed in air. Upon rotation of the section, the polarizer only inserted, there is a position in which the tourmaline is almost black. The elongation of the tourmaline is then at right angles to the vibration direction of the nicol. The crystal is then aligned with its elongation parallel to the lateral cross hair and the polarizer rotated until it becomes dark. The instrument is so marked that the polarizer may be aligned at any time to the cross hair of the eyepiece.

As an accessory to the microscope it will be found helpful to have a gypsum or selenite plate which is cut of such thickness that, between crossed nicols, it gives an interference color which is red of the first order. This color is known as the *teinte sensible.* This plate is usually mounted between two pieces of glass for protection. It is also desirable to have a quartz wedge, cut so that one flat side is parallel to the principal axis and the other tapering at an angle of 5°. These two accessories are very useful in determining the optical nature of the birefringence and elongation of a mineral.

In examining minute grains for interference figures in convergent polarized light, a screen is useful in order that all light except that coming through the mineral may be cut out. In its simplest form this screen is a round disk with a center hole 1 mm. or less in diameter. It is placed upon the cap nicol, or in case the nicol is in the body of the tube, upon the top of the tube. The eye-piece is always removed to observe interference figures.[1]

For detailed descriptions of the most highly developed microscopes for the examination of soil minerals, the reader is referred to Rosenbusch [2] or Dana,[3] or to the trade catalogues.

TRANSMISSION OF LIGHT.

In the mineralogical determination of minute soil grains the most valuable diagnostics are optical. It will therefore be pertinent at this time to discuss somewhat briefly the manner of light propagation and its behavior in crystallized media.

In homogeneous bodies light is transmitted in a straight line, propagated by transverse waves normal to the direction of propagation. The velocity of light in air has been determined to be 186,300 miles per second. The velocity of light is dependent upon the chemical nature of the medium in which it is propagated, and in crystallized bodies, belonging to other than the isometric system, upon the direction. For instance, light travels faster in a vacuum than in air, faster in air than in water, and faster in water than in

[1] This is not necessary where the miscroscope is fitted with a Bertrand lens.
[2] Mikroskopische Physiographie der Mineralien, Erste Band, erste Teil, p. 167 et seq. (1905).
[3] A Text Book of Mineralogy, 1900, p. 183 et seq.

most solid media. This difference in rate of propagation is of great importance in the identification of soil minerals. We do not actually measure differences in the velocity of light in soil grains, but measure a constant which is dependent upon the velocity. This constant, which is inversely proportional to the velocity of light, is called the index of refraction.

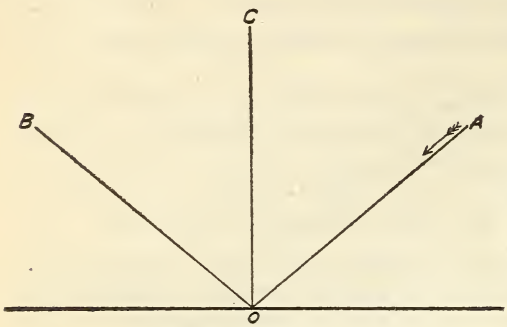


FIG. 4.—Reflection.

INDEX OF REFRACTION.

When light falls upon a polished surface, part of it is reflected. The incident and reflected rays are in the same plane, and the angle of incidence AOC (in fig. 4) is equal to the angle of reflection COB.

When light passes from one medium to another of greater or less optical density, the light is bent or "refracted" from its former path. This is due to the difference in velocity of the rays in the different media. The incident ray AO (in fig. 5) and the refracted ray OB are in the same plane. The ratio of the sine of angle of incidence AOC to the sine of the angle of refraction BOC' is a constant for any particular system, but varies with the chemical nature of the media, and is a measure of the difference in velocity of the light in the two media. This ratio of the sine of the angle of incidence to the sine of the angle of refraction is called the index of refraction and in isotropic bodies is independent of the direction of the transmitted light.

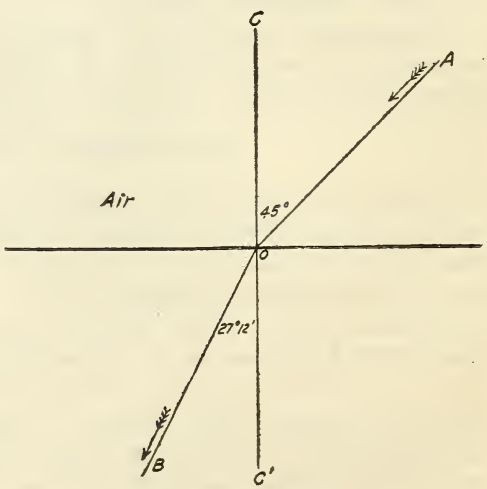


FIG. 5.—Refraction.

ISOTROPIC BODIES.

In all liquids,[1] in amorphous bodies, and in those crystallizing in the isometric system, the velocity of light is the same in all directions. If light be propagated from a center in such a body

[1] As an apparent exception to this, Reinetzer (Monat. f. Chem., 1888, IX, 435) first discovered an organic compound (cholesteryl-benzoate) having a definite melting point which as a liquid acted as an anisotropic body. Lehman studied several of these turbid liquids, which clear at a slightly higher temperature and lose their anisotropic nature. A comparatively large number of anisotropic liquids and so-called liquid crystals have been described in recent years.

and intercepted at any moment, the wave front will be a sphere; that is, all the rays will travel the same distance in every direction. Such bodies are called isotropic; that is, their optical properties are independent of direction.

ANISOTROPIC BODIES.

In contradistinction to isotropic bodies are the anisotropic ones, or those through which light travels at different rates in different directions. To this class belong all crystals other than those of the isometric system. A ray of light, having its waves of propagation in every possible plane when passing into an anisotropic body, is split into two rays which are propagated by vibrations normal to the direction of propagation, and at the same time the vibrations are in two planes at right angles to each other. These rays, however, are in the same plane with the incident ray, but are propagated at different velocities. Consequently each ray has an index of refraction distinct from the other. This phenomenon is known as birefringence or double refraction. It is plainly illustrated in the mineral calcite,

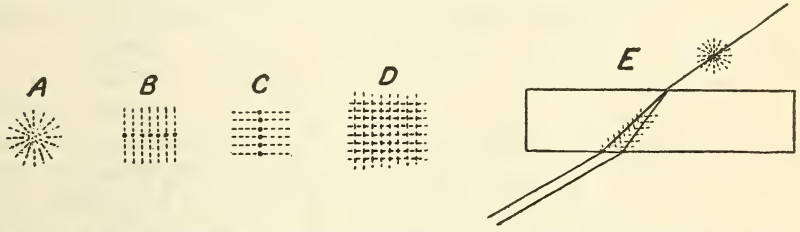


FIG. 6.—Ordinary and polarized light, and transmission of light through an anisotropic medium.

which (when transparent) may be placed over some printing and then shows a double image. This is due to the separation of the single incident ray into two refracted rays of unequal velocity, which reach the eye from two separate angles, forming two distinct images.

Ordinary light is transmitted by vibrations normal to the line of propagation, but the planes including these vibrations may be inclined at various angles to one another. When light passes through an anisotropic body, however, the two refracted rays have peculiar properties distinguishing them from rays of ordinary light. All of these rays are transmitted by transverse vibrations, one set of which is transmitted by vibrations in parallel planes and the other set by vibrations also in parallel planes but at right angles to the planes of the first set. This phenomenon is called polarization and the two sets of rays transmitted through anisotropic bodies are plane polarized and the planes of polarization are at right angles to each other.

In figure 6, *A* is a diagrammatic view of a bundle of rays which are propagated by transverse waves (dotted lines) which have no especial distribution. In *B* and *C*, on the other hand we have diagrammatic views of a bundle of rays with the transverse path in a series of parallel planes, in other words, polarized, and the planes of

polarization at right angles to each other. *D* illustrates two plane polarized rays superimposed one upon the other; that is, when incident angle is equal to 0°. *E* represents transmission of light through an anisotropic medium. The ordinary light as represented in the illustration is split into two plane polarized rays.

The use of polarized light is invaluable in the microscopic study of rocks and soil grains. The most acceptable and convenient method of preparing polarized light is by the use of a so-called nicol. The nicol is a piece of Iceland spar so constructed that in the passage of light through it the ordinary ray suffers total internal reflection and the extraordinary ray alone emerges. One nicol is placed in the substage of the microscope below the condensing system and the other above the objective, or in the case of a cap nicol, above the eyepiece. Light coming through such a nicol is plane polarized; that is, it is propagated by transverse vibrations which are in parallel planes. Consequently when the nicols are so arranged that the vibration planes of each nicol are parallel to each other light is transmitted. When, however, these planes are at right angles to each other they mutually interfere and no light is transmitted; the field is totally dark.

Whenever an isometric mineral such as garnet, fluorite, etc., is placed between crossed nicols, there is no appreciable difference in the phenomena observed; upon rotating the mineral the field remains dark. But when an anisotropic mineral is placed between the two nicols as they are crossed light is transmitted, the mineral often appears light colored in a dark field. The mineral so modifies the vibration plane of the light emerging from the polarizer that part of the light transmitted through the mineral grain is permitted to emerge through the upper nicol.

The polarizer in the substage does not interfere with observations in ordinary light except that it reduces the transmitted light by one-half. In fact its use is advantageous in the determination of indices of refraction, and it is necessary in the study of pleochroism, since it confines the light to vibrations in one plane. When a mineral grain is brought to the position of extinction between crossed nicols, and if the analyzer be removed, the light passing through the grain will be transmitted by vibrations in only one of the two vibration planes of the mineral. Thus in this position it is possible to determine the fundamental pleochroic color transmitted by vibrations in each of these two directions and to determine separately the refractive indices of these two vibration directions.

In a rotation of an anisotropic mineral through 360° there are four positions in which the light transmitted through the mineral between nicols completely disappears and the field is uniformly dark. This position is called the position of extinction. The angle between this position and a crystallographic boundary, cleavage

face, etc., is called the angle of extinction and is a very important means of distinguishing monoclinic and triclinic minerals from each other and from those of the tetragonal, hexagonal, and orthorhombic systems. These last three systems show parallel extinction; that is, the crystallographic boundary and the vibration planes of the nicols coincide when the mineral is at the position of extinction. A mineral is at the position of extinction when the positions of maximum and minimum indices of refraction of that particular section are coincident with the vibration planes of the nicols.

In any one direction through an anisotropic medium two rays may be propagated, which rays are produced by vibrations at right angles to each other and normal to the direction in which the rays are passing. Suppose a plane be passed through the direction of the ray, normal to it, and on this plane and in the two directions of vibration there be plotted points at distances equal to the reciprocals of the indices of refraction of each of the rays. Suppose further that this process be repeated for all possible directions passing through any given point within the medium. Then the points marking the reciprocals of the refractive indices will lie in the surface of a solid. If the medium is uniaxial the surface will be an ellipsoid of rotation. If, however, the medium is biaxial, this surface will be an oblate ellipsoid.

In this ellipsoid the axes correspond to the maximum, minimum, and mean velocity of the rays transmitted normal to their direction. Any section of the ellipsoid will be an ellipse (in certain cases a circle) and the two rays of light propagated normal to the section through the mineral will have their vibration directions coincident with the major and minor axes of the ellipse and the velocity of the two rays to each other will be as the axes of the ellipse.

Light traveling in any given direction through a mineral will then be represented by the sectional ellipse formed from the ellipsoid according to the orientation of the mineral, and the vibration directions of the two rays will be the major and minor axes of the elliptical cross sections.

The optical ellipsoid, therefore, enables one to determine the vibration direction (position of extinction between crossed nicols) and the index of refraction for each of the rays of light propagated in any particular direction through an anisotropic medium.

The three axes of the optical ellipsoid at right angles to one another correspond to the velocities of rays propagated in directions at right angles to the axes but vibrating in the directions of the axes. In the biaxial ellipsoid there will be a major (maximum value), minor (minimum value), and mean axis at right angles to each other.

In the isometric system these three axes are equal, since in any direction the velocity of light is the same, and the wave front is a sphere.

In the tetragonal and hexagonal crystallographic systems two of these axes are equal and the third axis is greater or less, and accordingly the mineral is positively or negatively birefringent, as will be described presently. This third axis is always, in these systems, coincident with the direction of the vertical crystallographic axis *ć*. The two equal axes are in the same plane as the horizontal crystallographic axes. Light transmitted parallel to the vertical crystallographic axis *ć* is propagated by vibrations normal to this axis; that is, the vibrations are in the plane of the equal axes; and since there is no difference in the velocity of the rays the light will pass as through an isotropic body. Light transmitted in any other direction than that of crystallographic axis *ć* suffers double refraction in that the ray is separated into two rays which are propagated at different velocities by transverse waves. Both of these rays are polarized and the planes of polarization are at right angles to each other.

In the tetragonal and hexagonal systems one of these rays will always have the refractive index (velocity) of the ray transmitted parallel to crystallographic axis *ć*. This ray is called the ordinary ray, and its refractive index (ω) and velocity are independent of the direction of propagation through the mineral. The value of the refractive index for the extraordinary ray is dependent upon the direction of the propagation of the ray. It varies from a value approaching that of the ordinary ray when the direction of the light is almost parallel to the vertical axis to a limit when the light is transmitted perpendicular to vertical axis *ć*, which is a maximum in positive minerals and a minimum in negative minerals. If the index of refraction (ω) of the ordinary ray is less than that of the extraordinary ray, the mineral is arbitrarily designated as positively birefringent $\omega < \varepsilon = +$. Conversely, if the index of refraction of the ordinary ray is greater than that of the extraordinary ray, the mineral is designated as negatively birefringent $\omega > \varepsilon = (-)$.

Basal sections of these minerals do not have any effect upon parallel polarized light, so that in crossed nicols the field remains dark. If the light from the polarizing nicol be passed through a condensing lens before entering the mineral, the incident parallel rays are deflected and the rays passing through the mineral grain will be inclined to the crystallographic axis.

In this case as the inclined rays are no longer normal to the optic section the ray is split into two rays, one with refractive index ω, ordinary ray, the other with an index value slightly greater or less, as the mineral is positive or negative. Between crossed nicols a feeble light filters through. If this phenomenon be observed with a microscope fitted with a high-power objective $\frac{1}{8}$ inch or less focal length and the eyepiece be removed, one sees in the tube of the microscope an interference figure. With minerals of these two sys-

tems the figure is "uniaxial;" that is, there is a figure of two dark brushes at right angles (see fig. 7) to each other and parallel to the vibration planes of the nicols. If the section or grain is thick or the birefringence of the mineral high, then symetrically arranged around the cross are rings, which rings are variously colored with white light, but are alternate light and dark rings with monochromatic light. Upon rotating the stage of the microscope, if the center of the cross is coincident with the optical center of the microscope, the cross and rings remain stationary. If center of cross is slightly to one side of the optical center, the center of the cross revolves in a circle around the optical center of the instrument, the dark bars or brushes retaining their position parallel to the vibration planes of the nicols. On account of this interference figure, minerals crystallizing in the hexagonal and tetragonal systems are called uniaxial and the interference figure distinguishes them from minerals crystallized in the other systems. The point of intersection of the two bars in the interference figure marks the emergence of the optic axis.

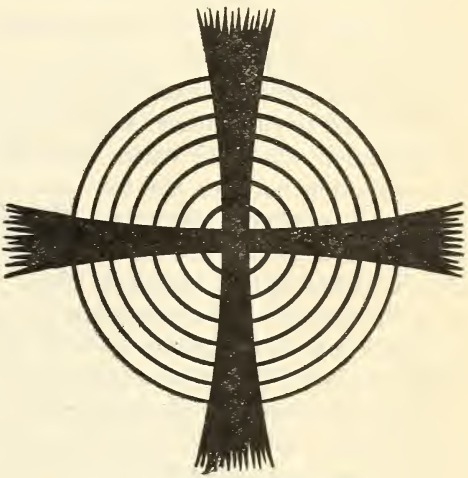


FIG. 7.—Uniaxial interference figure.

In minerals of the orthohombic, monoclinic, and triclinic systems the propagation of light is for convenience referred to three axes at right angles to each other, the so-called axes of ether elasticity in the oblate ellipsoid. It is customary to employ the following symbols:

a=vibration direction of the fastest ray, α=index of refraction of that ray.
b=vibration direction of the mean ray, β=index of refraction of that ray.
c=vibration direction of the slowest ray, γ=index of refraction of that ray.

It is, of course, obvious that the face of the advancing wave of light through an anisotropic medium lies in the surface of the ellipsoid, whose shape is determined by the three axes corresponding to the reciprocals of the indices of refraction. In the orthorhombic system the direction of these axes is coincident with the crystallographic axes. In the monoclinic system one ether axis (generally **b**) is coincident with the macro-axis *b*. The other two are therefore in the plane of crystallographic symmetry and variously inclined to the vertical axis and the clino-axis.

In the triclinic system there is no apparent relation between the crystallographic axes and the axes of the optical ellipsoid.

In the ellipsoid of three unequal axes corresponding to biaxial crystals, the axis of medium value (𝔟) is an axis of rotation. Cutting sections from the ellipsoid, it is possible to cut two sections where the larger axis of the sectional ellipse is so foreshortened that it equals 𝔟, the axis of medium value. These sections are circles. Light transmitted normal to these sections will be propagated by vibrations of equal velocity and therefore this section should act as an isotropic body and in polarized light between crossed nicols no light should be transmitted. Actually, in such a section, instead of darkness, there is a faint glimmer of light which persists through a complete rotation of the stage.[1]

With the microscope, if the convergent lens is introduced in the substage and the eyepiece removed, using $\frac{1}{6}$-inch objective or less, an interference figure is seen much like that of the uniaxial figure. Instead of two brushes, however, there is only one, and upon rotation of the stage this brush revolves about the center in the opposite direction to that of the rotation of the stage. The center of the brush is the point of emergence of the optic axis. The two optic axes are inclined to each other, and the angle between them is called the optic angle. Its value varies with the principal indices of refraction. The direction between the two axes and in the same plane with the optic axes is called a bisectrix. The bisectrix of the angle where $2V < 90°$ is called the acute bisectrix (Bx_a); the other, at right angles to this, is called obtuse bisectrix (Bx_o). The bisectrices are coincident with the axes of optical elasticity, and with the directions of vibration of the rays with maximum and minimum indices of refraction. The optic symbol, $2V$, always designates the acute angle.

The plane carrying the bisectrices and the optic axes is called the optic plane. When the acute bisectrix is coincident with the axis of greatest ease of vibration 𝔞, the mineral is said to have negative birefringence and conversely when axis 𝔠 is the acute bisectrix the birefringence is positive.

The orientation of the optical properties of a mineral can not be determined in parallel polarized light. Between crossed nicols all sections of anisotropic minerals transmit polarized light, except uniaxial crystals where light is transmitted parallel to the optic axis. In a complete rotation of 360°, extinction takes place four times when the direction of least vibration and greatest vibration planes of the section are coincident with the vibration planes of the two nicols, except when light is transmitted through a biaxial mineral in the direction of an optic axis.

[1] The explanation of this phenomenon may be found in Dana's Textbook of Mineralogy, p. 207.

COLOR OF MINERALS.

Generally speaking, the color of a mineral is not a safe guide in its identification. Occasionally, however, it has a considerable importance, and consequently it seems desirable to describe some of the principal color phenomena useful to the soil mineralogist.

It will be convenient to consider first colorless minerals and white ones. Most minerals in a pure condition are colorless, and many of the colored ones in very small particles, as when finely ground or as they occur in the fine silts and clays, appear colorless. Lack of color, however, should be distinguished from whiteness or opacity due to more or less complete total reflection, as shown by some powdered minerals or those made up of intertwining of very small individuals, or by very minute inclusions, as with milky quartz, for example. Generally, the white opaque minerals when immersed in a liquid having the same refractive index appear colorless or with their true color. Anomalous colors due to superficial coatings or inclusions are rather common, and in such cases the particles are frequently opaque. Their true character can usually be recognized under the microscope by cutting off the transmitted light and observing them in reflected light only.

The color of a mineral is frequently due to the presence of a very small amount of impurity. Often it varies greatly with the thickness of the particle and in extreme cases a strong-colored mineral in minute fragments may appear practically colorless. Frequently the color by transmitted light is quite different from that by reflected light, as in the case of many ferrous silicates which in larger grains are green by transmitted light and black by reflected light. Table V gives an arrangement of minerals with their characteristic colors, which is useful for the purposes of identification.

When polarized light is transmitted through a colored anisotropic mineral, rotating the stage of the microscope carrying such a section often causes a change in the intensity of the color, or even in the color itself. This property is known as pleochroism, and is characteristic of a few of the colored minerals, such as tourmaline, hornblende, epidote, etc. As pleochroism is due to the difference in absorption of the light waves in a crystal, it is not manifested by isotropic colored minerals, such as the garnets or spinels. The amount or magnitude of pleochroism varies with the nature of the mineral, upon the depth of color of the mineral, and upon the thickness of the mineral fragment. Recently Joly[1] has devised a method for the intensifying of pleochroism. By the use of mirrors, within a microscope polarized light passes through the mineral section then back again, which has the effect of doubling the thickness of the section.

[1] Joly. Proc. Roy. Dub. Soc., 9, 485 (1901).

TABLE V.—*Colors of minerals.*

Minerals.	Color-less.	White.	Gray.	Black.	Brown.	Red.	Yellow, orange.	Green.	Blue.
Leucite	x								
Pinite	x								
Topaz	x								
Barite	x								
Sanidine	x								
Tremolite	x								
Asbestos	x						x		
Gypsum	x								
Anhydrite	x								
Microcline	x								
Plagioclase	x								
Zeolite	x								
Aragonite	x								
Kaolin	x								
Analcite	x	x							
Meionite	x	x							
Vesuvianite	x					x	x	x	
Quartz	x								
Calcite	x	x	x						
Dolomite	x	x	x				x		
Magnesite	x	x	x				x		
Siderite	x				x		x		
Nepheline	x								
Eleolite	x							x	
Zoisite	x							x	
Sodalite	x								x
Fluorite	x								x
Melilite	x							x	
Iolite	x								x
Cyanite	x								x
Sillimanite	x					x			
Chalcedony	x					x			
Enstatite	x		x				x		
Muscovite	x						x	x	
Sericite	x						x	x	
Talc	x		x				x	x	
Diopside	x							x	
Olivine	x						x	x	
Titanite	x	x				x	x	x	
Actinolite	x							x	
Opal	x	x				x	x		
Glass	x		x		x	x	x	x	x
Nosean	x		x		x	x	x	x	x
Hauynite	x		x		x	x	x	x	x
Almandite	x					x			
Zircon	x	x					x		
Tourmaline	x		x		x		x	x	x
Apatite	x	x	x		x		x		x
Corundum	x				x	x			x
Andalusite	x		x			x			
Orthoclase	x	x	x			x	x		
Argillite		x	x	x	x			x	
Graphite				x					
Bitumen				x					
Carbonaceous material				x					
Magnetite				x					
Ilmenite				x					
Chromite				x					
Hematite				x	x	x	x		
Hypersthene				x	x			x	
Goethite					x	x	x		
Limonite					x	x	x		
Rutile					x		x		
Brookite					x	x	x		
Staurolite					x		x		
Bronzite					x		x	x	
Augite	x				x		x	x	
Diallage					x		x	x	
Hornblende					x			x	
Allanite					x	x			
Biotite				x	x		x	x	
Rubellite					x	x			
Phlogopite					x		x		
Pyrope						x			
Marcasite							x		
Pyrite							x		
Serpentine							x	x	
Chlorite								x	
Viridite								x	
Pleonast								x	
Hercynite								x	
Phosphorite									x

DETERMINATION OF INDICES OF REFRACTION.

In the sands the indices of refraction are determined by the inclined illumination method of Schroeder Van der Kolk. The method requires immersion oils or liquids of various indices. It is essentially a comparison of the index of the grain and the embedding material. With isotropic grains, in the nature of the case, there is only one index to be obtained. With anisotropic substances the index observed will depend upon the position or orientation of the particle with the microscope. The grains after immersion in oil are covered with a cover glass and brought into the field. The condenser lens is dropped a little and one finger is placed partly over the polarizing case—or reflecting mirror in the substage—throwing a shadow on one-half of the field. The stage of the microscope is so moved that the grain is in the shadow, but close to its boundary. There are three possible cases:

(1) The mineral grain has a bright edge which is toward the shadow. Then the index of the mineral is greater than that of the medium.

(2) The mineral grain has a bright edge away from the shadow. Then the index of the mineral is less than that of the medium.

(3) The mineral grain shows a blue edge toward the light and a red edge toward the shadow. Then the indices of the grain and medium are equal.

The use of a series of oils of definite indices of refraction makes readily possible the determination of the index of the grain. In order to determine the several indices in an anisotropic mineral it is best to use crossed nicols and rotate the grain to the position of complete extinction. The analyzer is then removed and the index of the grain in the direction parallel to the vibration plane of the polarizer is determined by trial as before. The section is then turned 90° and it is determined whether or not the other index is higher or lower. The same index is then determined by further trials in the several oils, due consideration being given to the orientation of the grains.

With this method it will be necessary to try out the microscope to find the best adjustment of the condenser system. For example, in the Fuess instrument the relations of the thin light edge may be completely reversed by removing the condenser or by elevating it to the highest point. The great value of this method of inclined illumination lies in the quickness and readiness with which determinations can be made.

In the determination of the index of refraction of silt grains it is necessary to use a higher magnification than that obtained by a ½-inch objective, so that Schroeder Van der Kolk's method can not be used. Becke's line method for the determination of the index of

refraction of silt grains is also a method of inclined illumination which requires oil immersion. The method is much the same as Schroeder Van der Kolk's, except that the difference in indices of oil and grain is more clearly perceived. When inclined illumination is produced by shading with the finger there is perceived at the edge of the grain a thin edge of light. Upon raising the tube of the microscope slowly with the fine adjustment this line of light, or "Becke's line," is seen to move into the grain or away from it. As the tube is elevated this line moves toward the substance with the higher index, and upon lowering the objective the reverse takes place. The adjustment of the condenser system is not as important in this method as in that of Schroeder Van der Kolk. The method is much more sensitive and consequently is used with the high-power objectives.

The phenomena of "relief" is closely connected with the index of refraction. In general it is a convenient means for preliminary determination of the index. When a soil grain is observed under a microscope the edges of the grain possess a very dark border. Upon immersion of the grain in water this border is diminished very much, but still is apparent. Upon immersion in oil the dark edges and the relief entirely disappear and the oil and grain appear as one when the indices are the same. In practice it is easy to "size up" the index by the relief. Minerals which possess an index much lower than the medium also give pronounced relief. An elevation of the tube will distinguish between these two cases by showing the movement of Becke's line.

EXAMINATION OF MINERALS IN PARALLEL POLARIZED LIGHT.

DISTINCTION BETWEEN ISOTROPIC AND ANISOTROPIC MINERALS.

After examination in ordinary polarized light for color, pleochroism, index of refraction, cleavage, and outline, the mineral soil grain is examined in parallel polarized light between crossed nicols. Immediately a distinction is made between isotropic and anisotropic minerals. Isotropic minerals, of which the more common in soils are fluorite, spinel, chromite, and the garnets, do not permit the passage of light between crossed nicols, while the anisotropic minerals will alternately admit and cut off the light four times as the stage of the instrument is rotated. Occasionally a mineral grain transmits polarized light, and in a rotation of 360° there is no extinction, or, possibly, only a diminution in the intensity of the already feeble transmission. It will be found that this mineral is biaxial and shows the emergence of an optic axis, i. e., has an aggregate polarization. Uniaxial minerals where the optic axis is parallel to the axis of the microscope will not transmit polarized light. These two orientations, however, are exceptional, and isotropic grains may be distinguished by observation

in convergent polarized light, as will be described later. A simpler way is to apply a gentle pressure upon the cover glass near the edge. The grains appear to rush about and readjust themselves. The same result is brought about less violently by tapping gently on the cover glass with a wire spatula. This manner of obtaining a different orientation of the mineral grain is very simple but an invaluable aid to the optical investigation of the very small soil particles.

BIREFRINGENCE.

In the previous discussion it has been shown that light is transmitted through anisotropic grains by two series of vibrations which give rise to two light waves, the planes of which are at right angles to each other. The velocities of these waves are unequal, so that when they emerge from the grain there is a definite phasal difference between them, which will depend upon the thickness of the grain, upon the difference in path of the two rays in the grain, and upon the difference in velocity of the rays. When the components of these two waves are reduced to vibrations in the same plane by the introduction of an analyzer, this difference in phasal relation brings about interference phenomena. Thus, in monochromatic light if the difference in phase is equal to a wave length or a whole number of wave lengths the waves mutually extinguish one another upon introducing the analyzer, and we have darkness (in crossed nicols) through a complete rotation of the stage. Any other difference in phase between crossed nicols will bring about a partial extinction of the light, which will vary with the inclination of the grain (rotation of the stage) to the vibration planes of the nicols. In the case where the principal vibration planes of the mineral are coincident with the vibration planes of the nicols the light is completely extinguished.[1]

Anisotropic minerals behave somewhat differently in white light. On account of the heterogeneity of white light, which consists of many waves of differing length and velocity, at no time is there an equal difference in phase for all wave lengths. Therefore, instead of having total extinction due to phasal differences, there is extinction for rays of definite wave lengths (colors). These variously colored rays which have been extinguished are essential to the formation of white light, so that by their elimination the light which is transmitted is colored. This color does not change upon rotating the stage, since the rotation of the stage does not change this difference in phase, but the intensity of the color changes from its maximum at the 45° position to zero (total darkness) at the position in which the vibration planes of the nicols and the mineral grain coincide.

[1] For fuller discussion see: Iddings, Rock Minerals, pp. 139-140.

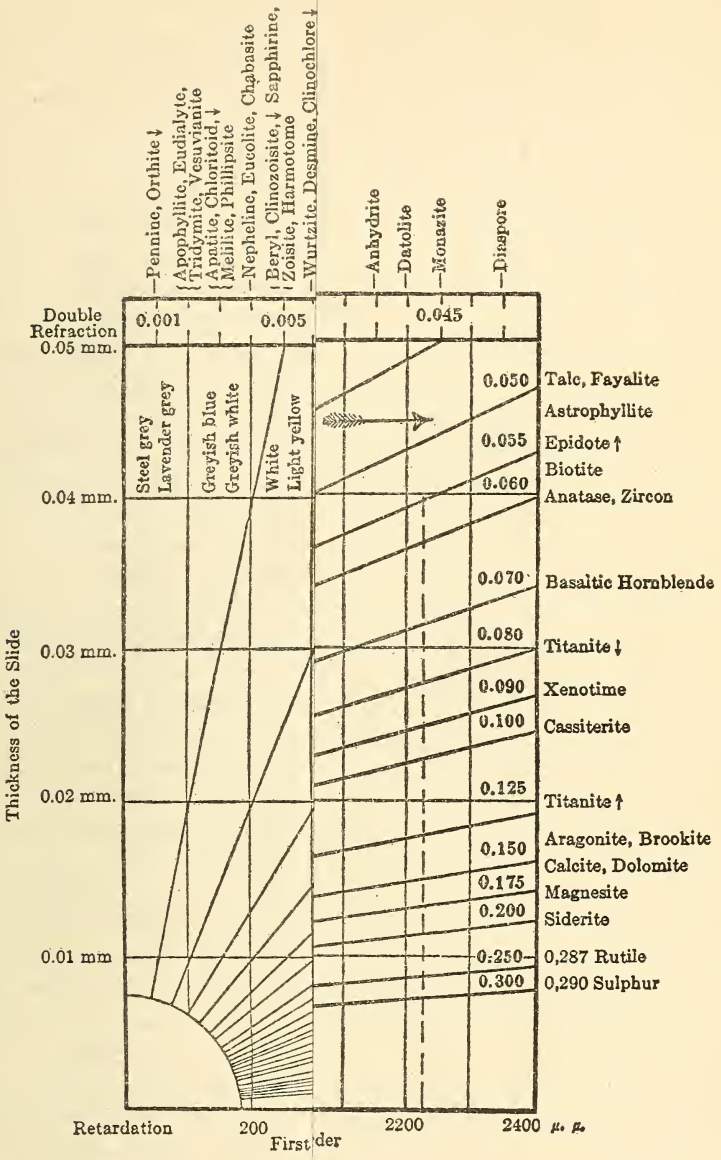
Thus, it happens that anisotropic mineral grains permitting the passage of light between crossed nicols appear as grains of various colors in a dark background. The interference color is dependent upon the thickness of the grain and in grains of equal thickness upon the difference in the indices of refraction (the birefringence) of the two sets of rays passing through the grain, and for changes in these values there are corresponding changes in the color observed between crossed nicols.

The interference colors obtained with anisotropic mineral grains vary from a dull gray and pale white with minerals of very small birefringence, rising with increase of birefringence through more brilliant colors of yellow, orange, purple of the first order, then lighter tints, blue-green, yellow, orange, and purple of the second order, to the still paler colors of higher orders. The very high orders of highly birefringent minerals are of a peculiar whitish color readily distinguished from the pale white of very low birefringence.

The birefringence of mineral grains is dependent in each mineral, as has been shown, upon the thickness of the grain and upon the direction of the light transmitted through the grain—that is, the optical orientation of the grain. In order, therefore, to determine the birefringence of a mineral it is necessary to know the orientation of the grain. To determine the thickness of the grain it is necessary to focus upon the base of the grain and then, using the fine adjustment, to focus upon the top of the grain. This difference in focus, read off from the graduations of the fine adjustment head in most microscopes, gives the apparent thickness of the grain. Owing, however, to the difference in path of the rays in the grain to those in air, it is necessary to multiply the apparent thickness of the grain by the mean index of refraction to get the true value. Whenever the orientation of the grain is such that the axis of the optical ellipsoid emerges, the birefringence is at its maximum.

Michel Levy has constructed a plot of maximum birefringence colors of the minerals. (See fig. 8.) In this plot the ordinates represent the thickness of the grain and the abscissas the birefringence colors due to difference in the indices. The colors starting at the origin mount up through the higher colors. In order to use such a table it is necessary to determine the thickness of the mineral grain as previously described, and this being found on the corresponding thickness ordinate of the plot, to carry this distance over the plot until the birefringence color of the mineral grain is matched.

The nearest oblique line having its origin at 0, is then followed to the border of the plot, where the difference in indices (birefringence) of the grain is obtained. If the grain is so oriented that the axis emerges, then this value is equal to the maximum birefringence of the mineral. The oblique lines (iso-birefringent lines) have at their


—Penninc, Orthite ↓
{Apophyllite, Eudialyte,
{Tridymite, Vesuvianite
{Apatite, Chloritoid, ↓
{Melilite, Philipsite
—Nepheline, Eucolite, Chabasite
{Beryl, Clinozoisite, ↓ Sapphirine,
{Zoisite, Harmotome
—Wurtzite. Desmine. Clinochlore ↓
—Anhydrite
—Datolite
—Monazite
—Diaspore
Double Refraction
0.001
0.005
0.045
0.05 mm.
0.04 mm.
0.03 mm.
0.02 mm.
0.01 mm
Thickness of the Slide
Steel grey
Lavender grey
Greyish blue
Greyish white
White
Light yellow
0.050
Talc, Fayalite
Astrophyllite
0.055
Epidote ↑
Biotite
0.060
Anatase, Zircon
0.070
Basaltic Hornblende
0.080
Titanite ↓
0.090
Xenotime
0.100
Cassiterite
0.125
Titanite ↑
0.150
Aragonite, Brookite
Calcite, Dolomite
0.175
Magnesite
0.200
Siderite
0.250
0,287 Rutile
0.300
0,290 Sulphur
Retardation
200
2200
2400 μ. μ.
First order

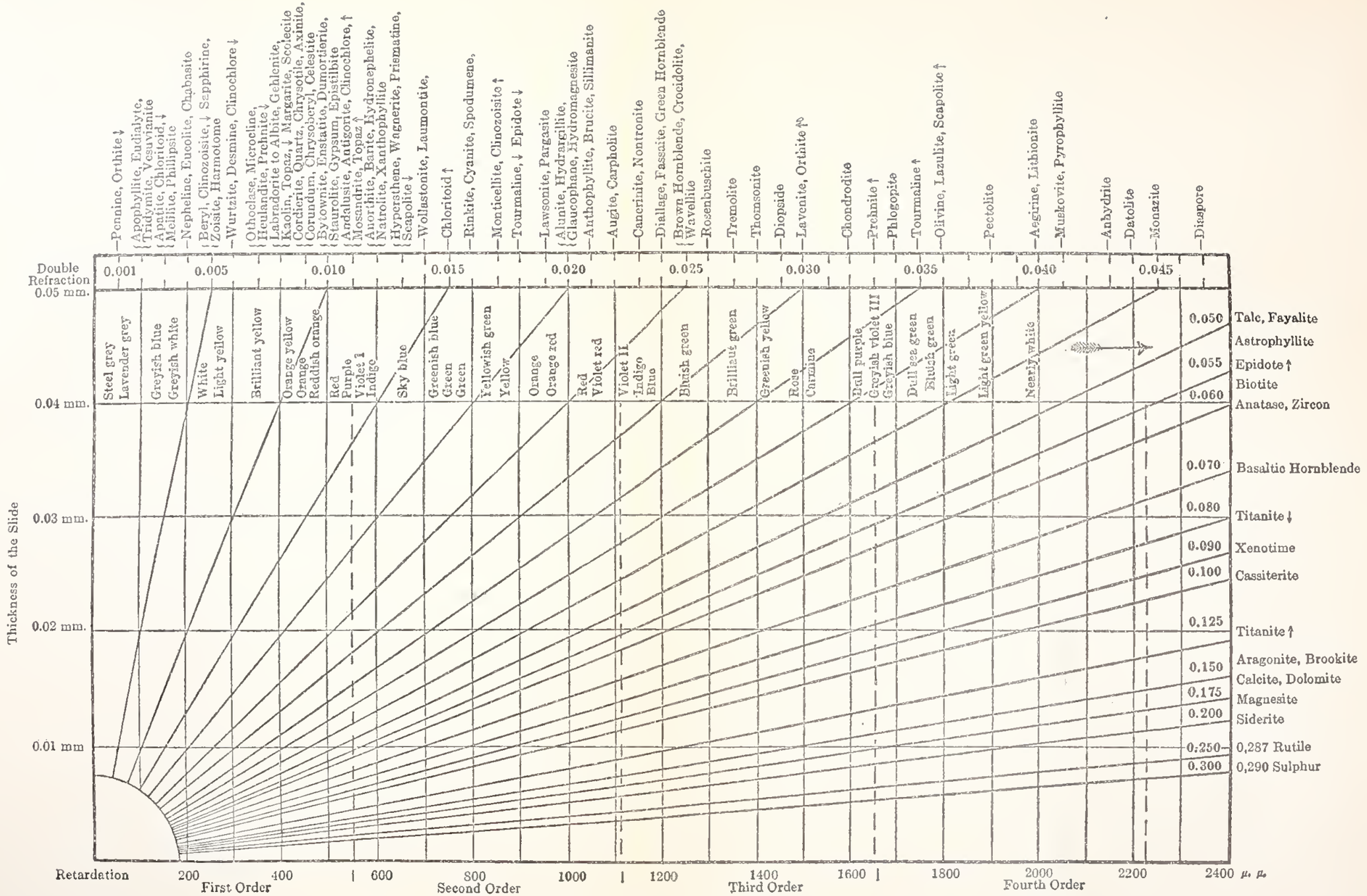


FIG. 8.—Plat of Maximum Birefringence Colors of Minerals.

[From Weinschenk—Clark's Petrographic Methods, McGraw-Hill Book Co.]

terminations the birefringent values and the minerals whose maximum birefringence ($\gamma—\alpha$) is equal to this value. The determination of birefringence of minerals by the use of the Michel Levy plot is limited in accuracy, however, to those minerals whose maximum birefringence is less than 0.050. Whenever this birefringence amounts to or is more than 0.050, the error involved is considerable and the determination of the separate indices is a more accurate method of determining the birefringence. The number of minerals are few whose birefringence is more than 0.050, the commoner ones of which are zircon, rutile, calcite, dolomite, and aragonite, minerals which can be readily distinguished by properties other than their birefringence.

The lower order birefringence colors, the grays and the pale whites, are very difficult to distinguish between crossed nicols. When, however, these colors are viewed in parallel nicols, distinction is very easily made and the proper position found upon the plot corresponding to the retardation.

For observation of minute birefringence the insertion in the instrument of a gypsum plate showing a birefringence color of purple of the first order is very valuable. A very feeble birefringence is sufficient to raise this color to the higher order blue when the vibration direction of the faster ray in the plate and grain coincide, and to lower it to yellow when the vibration direction of the faster ray of one is coincident with that of the slower ray of the other.

With the lower colors of birefringence the order of the color may be difficult to determine until the observer has had some practice. In these cases it is advisable to turn a section to the 45° position and then insert the quartz wedge, also at 45°. If the vibration direction **a** of the faster ray of both wedge and grain are coincident, then as the wedge is moved forward the interference color increases in order, the new color starting at the center of the grain and working toward the edge. If the vibration direction **a** of the faster ray of the wedge is coincident with the vibration direction of the slower ray in the grain, the converse takes place and the colors drop in order. The colors move from the edge toward the center. Finally the interference color will drop to a pale order, white, gray, and then to black. The insertion of the wedge is stopped at this point, the phasal difference in the wedge and grain being equal but opposite. On withdrawing the grain the interference color of the wedge is noted, and as the wedge is then slowly withdrawn the order of the interference color is also noted. Knowing the color, the order of the color, and the thickness of the grain, the birefringence is read off from the chart of Michel Levy. It is convenient at times to determine the order of the birefringence color in soil grains by counting from the extreme edge of the grain the number of times a particular color is repeated. Preferably purple is the color selected, since it marks the transition from one order spectrum to another.

Frequently certain minerals, such as tourmaline, hornblende, zircon, etc., on account of a prismatic crystallization or prismatic cleavage, show characteristic elongation. The extinction measured from this elongation is characteristic, as is also the optical nature of the elongation. That is, if the mineral possesses straight extinction and the elongated direction of the mineral is the direction of vibration $\mathfrak{r}$ of the slow ray, the elongation is positive. If the direction of vibration of the fast ray $\mathfrak{a}$ coincides with this elongation, the elongation is optically negative. The determination of the value of the vibration direction of the mineral grains has been previously described.[1]

In biaxial minerals, if the elongation is parallel to $\mathfrak{h}$, the optical elongation may be either positive or negative, accordingly as the opposite vibration direction is, $\mathfrak{a}$ or $\mathfrak{r}$. In some elongated minerals, as, for instance, augite, the direction of elongation is not parallel or nearly parallel to the vibration plane of the mineral, so that it has no characteristic optical elongation.

CHARACTER OF THE BIREFRINGENCE.

The optical character of a mineral, whether positive or negative, can be readily determined in parallel polarized light from the vibration planes of the grain if its optical orientation is known. The optical orientation is determined, however, in converged polarized light, as will be presently described.

If the section shows the emergence of an acute bisectrix, the vibration plane corresponding to the principal optical section will, in positive minerals, be the vibration direction $\mathfrak{a}$ of the faster ray; in negative minerals this direction will be the vibration direction $\mathfrak{r}$ of the slower ray. If the mineral grain shows the emergence of an obtuse bisectrix, then the principal optical section will, in positive minerals, with this orientation, be the vibration direction $\mathfrak{r}$ of the slower ray; in negative minerals it will be the vibration direction $\mathfrak{a}$ of the faster ray.

In mineral grains which show the emergence of the optic normal, if the direction of the acute bisectrix is the vibration direction of the slower ray $\mathfrak{r}$ the mineral is optically positive. If, however, this direction is the vibration direction $\mathfrak{a}$ of the faster ray, the mineral is negative.

With observation in parallel polarized light it is frequently found that in a homogeneous mineral there will not be simultaneous extinction throughout the mineral. There may be two cases. One is the so-called undulatory extinction frequently found in quartz, in which the extinction passes as a cloud through the mineral. This is due to certain mechanical forces which have at some time affected the grain,

[1] See p. 23 et seq.

notably great pressure, as in certain metamorphic rocks. The other case, of much more importance in mineral determination, is that in which a portion of the mineral shows extinction and at a certain angle another portion shows extinction. The line separating these two portions is nearly always a straight line. This effect is a result of a difference in orientation of portions of the grain due to twinning. Twinning is thus readily recognized between crossed nicols by the absence of uniform orientation. With the aid of the gypsum plate it is very readily shown that the two adjacent twins have a different optical orientation other than by their extinction angles. Twinning has a very important diagnostic value in mineral determination, especially in the case of the most abundant mineral types, the feldspars.[1] Another type of extinction or, rather lack of extinction, is to be found in the minerals with aggregate polarization. Some minerals, chlorite, kaolin, glauconite, etc., when they are formed, crystallize in minute grains in, around, and over each other, so that each grain interferes with the optical properties of others and the mineral is not crystallographically or optically homogeneous, but forms the so-called aggregates which, on account of the heterogeneous nature of their make-up, produce peculiar polarization colors, due to the mutual interference of the grains.

THE USE OF THE SELENITE PLATE AND QUARTZ WEDGE.

Light is transmitted through anisotropic minerals between crossed nicols by two vibrations at right angles to each other and of different velocities. One of the rays, upon emerging from the mineral, will have increased in phase a certain definite part of a wave length, which will depend upon the thickness of the grain and upon the difference in velocity of the two vibrations. As long as these waves are in different planes, no effect is observable. Whenever their components are reduced to a common plane, as by the introduction of an analyzer, this difference in phase of the two light waves causes interference phenomena. In ordinary white light a definite interference color is obtained, due to definite phasal difference in the two rays. If an anisotropic plate is superimposed with its vibration directions parallel to the grain, there are two phenomena observed. Whenever the vibration direction of the waves of maximum velocity of the grain and the plate coincide, the light passing from the grain through the plate is affected in the same manner as in passing through the grain itself, and there is an increase in phasal difference, and the effect is much the same as if the thickness of the grain were increased. If the grain is now rotated 90° and the vibration direction of the ray with the maximum velocity in the mineral grain coincides with the

[1] For further observation upon the twinning of the feldspars and how this property aids the identification of these minerals, the reader is referred to p. 60.

vibration direction of the ray with the minimum velocity in the plate, the amount which one wave has gained upon the other in traversing the mineral grain will be partly, entirely, or even more than compensated by the increased velocity of the slow ray of the grain and retardation of the fast ray of the grain while passing through the plate. The effect will be as though the grain were thinned. In case the phasal differences of the two rays of the plate and those of the grain are equal, there will be complete extinction, either in white or monochromatic light.

Practical use is made of these phenomena in determining the value of vibration directions of the two rays, which are propagated in an anisotropic grain. For practical purposes use is made of a selenite plate, showing an interference color of purple of the first order; and of a quartz wedge, one side of which is parallel to the crystallographic axis *ć* and the other side of which makes an angle with this axis. The selenite or gypsum plate is a side pinacoid cleavage face cut normal to **b** and to the optic normal; therefore, light is transmitted through this section by vibrations parallel to the axes **r** and **a**. The purple of the first order is the most sensitive interference color. A difference of phase induced by an anisotropic grain with faint birefringence will change the color to a higher-order blue if the vibration planes of the grain coincide with the corresponding planes of the plates. If, however, the vibration planes of the grain are at right angles to the corresponding planes of the plate, a lower order color, yellow, will be produced.

The orientation of the gypsum plate itself may be determined, as pointed out by Johannsen[1] from its appearance in converged polarized light. The center of the field is a purple. Toward the edge of the field this color turns to blue in two opposite quadrants and to yellow in the other two. The line joining the two yellow quadrants is the direction of the acute bisectrix, and since gypsum is positively birefringent, this direction is **r**. The vibration direction **b** is at right angles to this.

The vibration directions of the gypsum plate being known, the orientation of the relative value of the vibration planes of the quartz wedge is determined. The gypsum plate is used as a section upon the stage and rotated to the 45° position. The quartz wedge is now inserted in the 45° position and the change in interference color noted. If the vibration planes of the fast rays coincide, then the purple of the first order mounts up to the higher orders. If the fast ray of the gypsum plate is coincident with the slow ray of quartz wedge, the interference color falls, as the wedge advances, through yellow, white, gray, and then to darkness when the phasal differences

[1] Determination of rock-forming minerals, Wiley and Son, 1908, pp. 26, 516.

of the quartz wedge and gypsum plate are equal and opposite. The colors rise again if the wedge is inserted further.

The gypsum plate is used in determining the nature of birefringence and of the elongation of minerals whose birefringence is low. The quartz wedge is used for the same purpose in minerals whose birefringence are of the higher orders. The quartz wedge is also used to determine the order of interference colors. To use the quartz wedge for this purpose the mineral grain is turned to the 45° position, when the maximum light passes and the quartz wedge is inserted. If the direction of the vibration of the fast ray of the grain and the wedge coincide, then as the wedge advances there will be an increase in the order of the resulting color. The grain should be rotated until the color falls with the insertion of the wedge, and the latter advanced to darkness, when the phasal difference of the rays in the grain are compensated by the quartz wedge. The grain is removed, the color of the wedge noted, and the wedge withdrawn slowly, that the order may be noted.

With grains of high birefringence there are at the edges of the grain concentric rings of color. Upon insertion of the wedge, when the vibration directions of the fast rays of the grain and the wedge coincide these bands or rings seem to form at the center of the grain and expand toward the edge of the grain. Conversely, when the vibration directions of the grain and wedge, respectively, are opposed these concentric rings contract from the edge toward the center. Knowing the orientation of the grain as determined in convergent polarized light, the optical value of the vibration directions as found by the quartz wedge, then the optical character of the mineral is known.

EXAMINATION OF MINERALS IN CONVERGENT POLARIZED LIGHT.

Important means of identifying the soil minerals are the determination of the crystallographic system together with the determination of certain optical constants. Aside from the isometric system, these optical constants vary with the direction of the light in the mineral grain. It is therefore necessary to determine the orientation of the grain, to determine in what direction the light is transmitted, and to correlate intelligently the phenomena observed.

The orientation of the mineral grain is determined by the use of convergent polarized light. In convergent polarized light interference figures are obtained which distinguish uniaxial and biaxial crystals. The interference figures vary not only with the nature of the crystal but with the direction of the light in relation to the axes of optical elasticity. It is important therefore to correlate the phenomena observed in convergent polarized light with the axes of optical elasticity and with the crystallographic form.

ISOTROPIC MINERALS.

Isotropic minerals behave in convergent polarized light as in parallel polarized light. No light passes when placed between crossed nicols. Uniaxial minerals, when light is being transmitted parallel to the optic axis, behave as isotropic substances in parallel light, but in convergent light they give interference figures.

UNIAXIAL MINERALS.

The interference figure obtained in uniaxial crystals when the light is transmitted *parallel* to the optic axis, or when the direction of transmission is but slightly inclined to the optic axis, has been described on page 23. When the inclination of the optic axis to the section increases so that the emergence of the axis takes place outside of the field, then in a revolution of the stage there is seen only the interference bars moving broadside across the field parallel to the vibration planes of the nicols. The movement of the optic axis, though invisible, is in the same direction as the revolution of the stage. The greater the inclination of the optic axis to the plane of the section, the less distinct the bar, also the less the birefringence of the mineral and the more indistinct the interference figure and bar.

The interference figure obtained from the uniaxial mineral when the light is transmitted *normal* to the optic axis has a rather indistinct appearance. As the stage carrying the mineral is rotated, there are certain positions in which two hyperbolas will flash into the field from opposite quadrants, arrange themselves cruciform, and then quickly disappear in adjacent quadrants. As the rotation of the stage is continued, presently the phenomena of the hyperbola are repeated in the next quadrant. In a rotation of the stage through 360°, these phenomena occur four times, with a duration in each quadrant amounting to about 10° rotation.

Assuming that the progression of the hyperbola follows that of the rotation of the stage, namely, that the hyperbola appear in I and disappear from II, it is found empirically that the direction of the line separating the entering and departing hyperbola is the direction of the optic axis.

BIAXIAL MINERALS.

The interference figures of biaxial minerals (Fig. 9) will depend upon the direction of the light transmitted through the mineral grain. There are four important directions in biaxial crystals in which characteristic interference figures are obtained, namely, when light is transmitted in the direction of (1) The acute bisectrix, (2) The obtuse bisectrix, (3) The optic normal, (4) The optic axis.

If light is transmitted through a biaxial mineral in the direction of the acute bisectrix, and the stage be rotated to a position of extinc-

tion in *parallel* polarized light, then the interference figure obtained in *convergent* polarized light is a cross of two unequal dark brushes, parallel to the vibration planes of the nicols. Upon rotating the stage to the 45° position this cross dissolves into two hyperbola. The convexity of these depends upon the angle of the optic axes. The convex sides of the hyperbolas are toward the acute bisectrix. If the grain be thick or the birefringence high, about each of the axes there is a series of concentric rings variously colored in white light, or alternate white and black in monochromatic light. These rings, as they approach those of the other optic axis, form *lemniscates*. The dark brushes revolve about the optic axes in a direction opposite to that of the stage. The optic angle may be so large that the optic axes will not emerge in the field, but nevertheless the brushes are

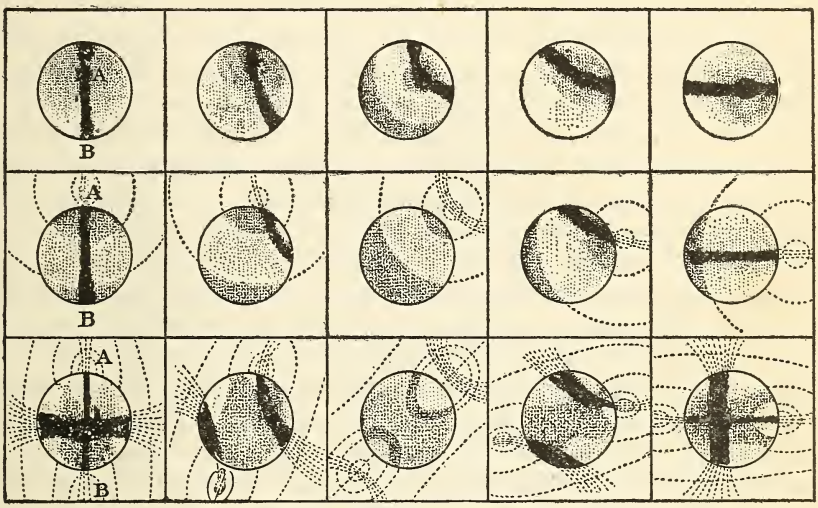


FIG. 9.—Biaxial interference figures.

seen, except possibly in the 45° position, when the lemniscates only are visible.

The interference figure obtained when light is transmitted through a mineral in the direction of the obtuse bisectrix is much the same as that obtained when light is transmitted in the direction of the acute bisectrix. With the obtuse bisectrix, however, the angle between the optic axes is so great that they emerge beyond the field, so that the hyperbola enter the field as a cross, which then opens, and they depart again. The amount of rotation of the stage necessary to bring the hyperbola from the position tangent to the field to the cross is a measure of the optic angle of the mineral and is a means of distinguishing the acute from the obtuse bisectrix and from the optic normal. The hyperbolas formed when the light is transmitted in the direction of the obtuse bisectrix are not as clearly defined as those formed when the light follows the acute bisectrix.

When the optic angle approaches 90° it is difficult to distinguish the acute and obtuse bisectrices. The best means is to find the stage rotation necessary to bring the hyperbolas from the position where they are tangent to the field to that position in which they form a cross at the center of the field. This rotation will depend upon the microscope and the objectives used. For doubtful cases it is well to calibrate the microscope for the several objectives by determining the rotations corresponding to the optic angles of known mineral sections. The optic angle of the mineral under inspection is then determined graphically by interpolation of the rotation necessary to bring the hyperbolas from tangent to the field to the position of the cross.[1]

The interference figure obtained in a biaxial mineral grain when the light is transmitted in the direction of the optic normal (that is, the axis of optical elasticity, which is normal to the plane carrying the bisectrices of the optic axes) is similar to the one obtained from uniaxial grains where the light is transmitted normal to the optic axis. In a rotation of the stage of 10° or thereabouts, two hyperbolas enter the field from opposite quadrants, form a very indistinct cross, and emerge in the adjacent quadrants. Assuming that the hyperbolas follow in the direction of rotation of the stage, it is found that the acute bisectrix lies in the direction of the line separating the entering and emerging hyperbolas. It is not possible to distinguish, however, the interference figure from that obtained with uniaxial crystals where the light is transmitted normal to the optic axis.

The phenomena observed in biaxial crystals when light is transmitted in the direction of one of the optic axes has been described on page 24. The interference figure is a single eye through which a dark brush passes. When this brush is coincident with the vibration planes of the nicols it is a straight line; at the 45° position it is at the point of maximum curvature and forms a hyperbola, the convex side of which is toward the acute bisectrix. The convexity of this brush varies with the optic angle, and where this value approaches 90° the brush becomes a straight line revolving in the opposite direction to that of the stage. If the birefringence of the mineral grain is high or the grain thick, this eye will be surrounded by concentric rings, variously colored in white light, alternate black and light in monochromatic light.

OPTICAL CHARACTER.

The selenite plate and quartz wedge are used in conjunction with the interference figure obtained in convergent polarized light to determine the nature of birefringence. In general, where the bire-

[1] See Wright, Am. Jour. Sci., 17, 385 (1904).

fringence is low or the mineral grain very thin, as is the case with the silts, the selenite plate is the more valuable. Where the birefringence is high, or where the grain is thick enough to show "rings," the quartz wedge is more valuable.

A selenite plate inserted in the 45° position will modify the uniaxial interference figure in such a manner that two opposite quadrants will be colored blue and the other two opposite quadrants yellow. Where the vibration direction r of the selenite plate is at right angles to the length of the plate, as is usual, the blue color will appear in minerals with positive birefringence in the upper right hand and the lower left hand quadrants (NE. and SW.); the yellow color will appear in the upper left hand and lower right hand (NW. and SE.). This color "reaction" is of great value, since it is not necessary that the axis emerge in the field if the bars of the interference figure are seen crossing the field. In this case the determination of the quadrants is easy and therefore also the birefringence.

With negatively birefringent minerals the converse is true, namely, that the yellow color occurs in the NE. and SW. quadrants and the blue color in the NW. and SE. quadrants.

With minerals of high birefringence, where the interference figure is surrounded by rings, a quartz wedge is used. The orientation of the quartz wedge is such that the vibration direction r is parallel to the short side of the plate, and if the wedge is inserted at the 45° position, the rings of the interference figure contract in the case of minerals with positive birefringence in the NE. and SW. quadrants and expand in the NW. and SE. quadrants. In other words, with positive minerals the circles move toward the axis in the NE. and SW. quadrants and away from the axis in the NW. and SE. quadrants. In the case of minerals with negative birefringence, the rings move toward the axis in the NW. and SE. quadrants and from the axis in the NE. and SW. quadrants.

In case the optic axis emerges outside of the field (as with a cleavage fragment of calcite), the orientation of the quadrants may be determined by the curvature of the rings and the optical nature of the birefringence by the movements of the rings.

In determining the nature of birefringence of *biaxial* crystals from their interference figures, it is usual to rotate the stage to the 45° position (the position at which the hyperbolas are most widely separated) so that the vibration planes of the mineral grain and the accessory plate coincide. With the insertion of the plates or wedges the difference in interference figures due to the thinning and thickening effect of the accessory plates are observed.

The effect of the insertion of the selenite plate at the 45° position upon a biaxial interference figure, also at the 45° position, is quite similar to that in the case of uniaxial figures. In the case of positive biaxial minerals when the hyperbolas are in the NE. and SW.

quadrants, upon inserting the selenite plate, the concave side of the hyperbola is colored blue and the convex side (toward acute bisectrix) yellow. If the hyperbolas are in the NW. and SE. quadrants, the concave side of the hyperbola is yellow and the convex side blue.

In the case of negative minerals this color diagnostic is of the reverse nature; that is, the hyperbolas in the NE. and SW. quadrants are colored so that the concave side of the hyperbola is yellow and convex side blue. When the hyperbolas are in the NW. and SE. quadrants the convex side is yellow and the concave blue.

The same effect would be produced if the uniaxial interference cross dissolved and the adjacent sides of the cross united to form hyperbola. The hyperbolas would limit the color on their concave sides. The hyperbolas of biaxial interference figures are at their maximum curvature at the 45° position and the convex side is toward the acute bisectrix. Thus the position of the hyperbolas with respect to the four quadrants is readily found and the nature of the birefringence easily determined with the assistance of the selenite plate. Essentially the interference figure of a uniaxial mineral is a limiting case for that of a biaxial mineral, where the optic angle approaches zero. Recognition of this fact will greatly facilitate the practical use of the selenite plate and the quartz wedge as the phenomena of uniaxial and biaxial minerals grade into one another.

The optical nature of the biaxial minerals whose interference figures show rings is determined with the quartz wedge. The stage is rotated until the figure is at the 45° position and the quartz wedge inserted. When the optic axes emerge in the NE. and SW. quadrants and the quartz wedge is inserted, in the case of positive minerals the rings expand from the optic axes, form lemniscates, and continue to expand. With negative minerals this action is opposite, the lemniscates contracting to form circles and these again contracting toward the optic axes.

With the optic axes emerging in the NW. and SE. quadrants the phenomena observed is the reverse of the above.

Where the acute bisectrix emerges outside of the field the orientation is obtained from observation of the optic axial hyperbola, and the quartz wedge then used to determine the birefringence.

ADJUSTMENT OF MICROSCOPE.

Observation in convergent polarized light discloses the orientation of the mineral grain. This observation is made with a high power objective, $\frac{1}{5}$-inch or less. The microscope is focused upon the grain and the condenser is raised to its highest point, almost touching the slide. The eyepiece is removed to observe the interference figures. Before the eyepiece is removed the microscope is

adjusted so that the mineral grain will remain in the center of the field during a complete rotation of the stage. This is important for successfully procuring interference figures from minute grains. With the fine silt grains it is necessary to use a higher power objective, $\frac{1}{10}$-inch or as high as $\frac{1}{15}$-inch, with oil immersion, and here the centering of the stage is of utmost importance. In order that the interference figure may have a better or less obscure outline, it is advisable in all cases, and necessary in some, that a stop or screen be provided which will effectually exclude from the eye all rays except those which have gone through the mineral grain. This is accomplished by placing on the top of the microscope a little disk, blackened, in which a minute hole is cut, so that only rays from the center of the field are seen. The small silt grains and most of the minerals less than 0.05 mm. diameter do not show the concentric circles and lemniscates around the optical axes, only dark brushes appearing.

ORIENTATION AND BIREFRINGENCE.

The birefringence determined in parallel polarized light varies as has been pointed out above with direction of transmission of the light in the mineral. The orientation of the mineral is determined in convergent polarized light, and it is necessary, therefore, to correlate birefringence which shall have a determinative value, i. e., characterize the mineral.

Suppose a birefringence of 0.005 is observed. Then if the mineral is positive, and the light is transmitted in the direction of the acute bisectrix, the light vibrations are in the directions of the axes of the optical ellipsoid, $\mathfrak{b}$ and a, the index of vibrations of these rays are β and α. Consequently, $\beta-\alpha=0.005$. If, however, the light is transmitted in the direction of the obtuse bisectrix $\mathfrak{a}$ then the vibrations are in the directions $\mathfrak{b}$ and $\mathfrak{r}$, and $\gamma-\beta=0.005$.

Should the mineral be negative, and the light transmitted in the direction of the acute bisectrix $\mathfrak{a}$ then the vibrations are in the directions of $\mathfrak{b}$ and $\mathfrak{r}$, and $\gamma-\beta=0.005$. With a negative mineral and the light transmitted in the direction of bisectrix c the vibrations are in the directions $\mathfrak{b}$ and $\mathfrak{a}$ and $\beta-\alpha=0.005$.

In either positive or negative minerals if light be transmitted in the direction of the optic normal b, the vibrations are in the directions of $\mathfrak{a}$ and $\mathfrak{r}$ and $\gamma-\alpha=0.005$.

ORIENTATION WITH A GLASS HEMISPHERE.

It is often desirable for determinative purposes to know the system in which a mineral or chemical salt crystallizes but where the substance is in such small particles that convergent polarized light is inapplicable. This may be determined without the use of convergent polarized light by the use of a polarizing microscope, owing to the

difference in action of each of the crystal systems upon parallel polarized light. Use is made of a simple device, a *halbkugel*, first described by Schroeder van der Kolk.[1] The *halbkugel* is a glass hemisphere the flat surface of which is ground smooth.[2] This *halbkugel* is placed in position, round end down, in the opening in the center of the microscope stage. The mineral under examination is placed on the flat surface. With this simple instrument it is possible to rotate the mineral grain or crystal through three axes, and secure any desired orientation.

To distinguish isotropic grains from uniaxial grains where the light is transmitted parallel to the optic axis, it is only necessary to tilt the *halbkugel* and then to rotate the stage between crossed nicols. If the

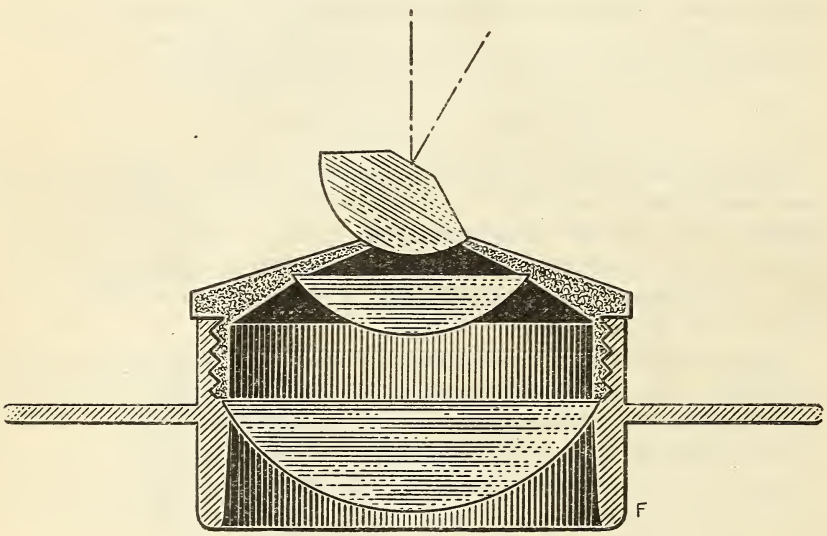


FIG. 10.—The ten Siethoff lens.

section is anisotropic, extinction phenomena are noted, as in regular anisotropic grains. To distinguish hexagonal, tetragonal, and orthorhombic crystals with parallel extinction from monoclinic minerals which show parallel extinction sections in the zone of symmetry, the stage is rotated to extinction, then the *halbkugel* is tilted around the axis parallel to the elongation of the mineral. Monoclinic crystals will no longer show parallel extinction, because by tilting the grain the crystal is no longer in the plane of symmetry.

To distinguish orthorhombic needles from hexagonal and tetragonal, the stage is rotated to the 45° position and the *halbkugel* is tilted upon its axes. Change in the birefringence or in the optical character of the elongation will show the mineral to be orthorhombic. No change in birefringence or optical character of any direction with

[1] Zeit. für Krys., 29, 401 (1898).

[2] The author has prepared a satisfactory "halbkugel" by grinding down the ball of a desiccator top.

tilting of the mineral will indicate either the tetragonal or hexagonal system.

The development of the use of the glass hemisphere in orienting a mineral fragment under the microscope has led to the construction of other devices, such as the "universal-tisch." These have become extremely valuable in mineralogical work, especially for researches upon such fragments as are found in the soil. But for most cases and where identification of the mineral species is the primary purpose, the glass hemisphere will prove quite as satisfactory and far easier to manipulate than the expensive and complicated devices necessary for quantitative measurements.

The ten Siethoff lens is a *halbkugel* combined with a condenser lens and so constructed that interference figures may be obtained in addi-

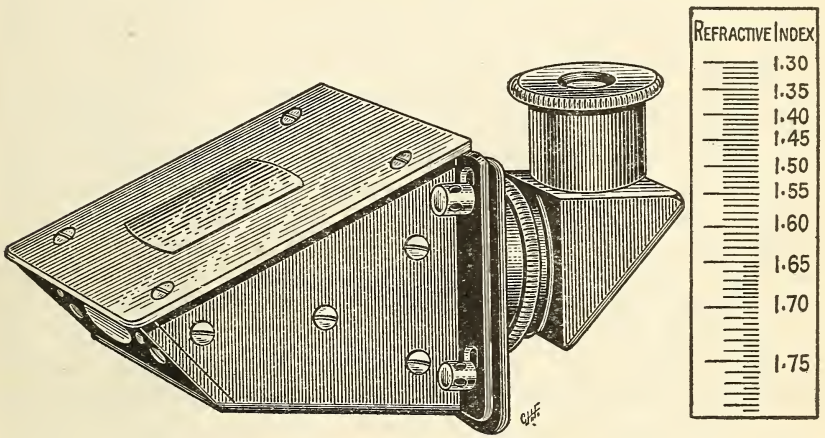


Fig. 11.—The Herbert Smith refractometer.

tion to the change in orientation accomplished by the rotation of the *halbkugel*. It sits in the aperture upon the center of the stage and has an advantage over the *halbkugel* in that it can be used with high-power objectives, since the object on the Siethoff *halbkugel* may readily be centered by moving the condenser back and forth on the stage, limited, however, by the flange of the instrument. Figure 10 is an illustration of a Siethoff lens.

IMMERSION OILS.

With the development of immersion methods, Thoulet solution of various concentrations has been used as an embedding material. This solution, however, has not been found useful for general application. Evaporation in the bottle and upon the slide causes great variations in the index so that it possesses little advantage as an embedding material. An ideal embedding material would be non-volatile, colorless, and have little or no dispersion. Schroeder van der Kolk early employed organic compounds, and from these, several of which belong to the etheral oils, a series of oils or embedding

liquids of graded indices may be obtained. Some of these oils with their indices follow:

	Index.		Index.
Cedar oil	1.516	Monochlornaphthalene	1.639
Clove oil	1.544	Monobromnaphthalene	1.658
Cassia oil	1.600	Methylene iodide	1.74
Monochlorbenzene	1.527		

From these compounds a series of oils differing from each other by 0.01 or 0.005 may be obtained. The oils are kept in dropping bottles and are protected from light by painting the bottles with a mixture of lampblack and shellac in alcohol. This is necessary in order that the decomposition of the oils be prevented. The dropping bottles are covered with a glass shield, also painted black, or some similar device. The series of oil mixtures are calibrated either on an Abbe refractometer, or above 1.7, by an Abbe crystal refractometer. A compact, efficient, and inexpensive refractometer for use in the determination of indices of refraction of both oil and minerals is that now made by T. H. Steward, of London, illustrated in figure 11. This instrument has a range of from 1.3 to 1.79, scale divisions to 0.01, which by estimation can be read to 0.002. It is advisable that the oils be checked every three or four months for deterioration and the index redetermined. Cassia oil decomposes readily, has a high dispersion, and is fairly high colored. Methylene iodide oxidizes readily and iodine is set free. This may be removed by washing with caustic or by using pieces of metallic copper, which unite with the free iodine. In tables from Schroeder van der Kolk are given the indices of certain compounds. These values can not, however, be taken as absolute, for the indices vary with the purity of the material. The following is the list of oils prepared and found useful in soil work:

	Index No.
Cedar oil	1.51
Mixtures of clove and cedar oil	1.51, 1.52, 1.53, 1.54
Mixtures of clove and cassia oil	1.55, 1.56, 1.57, 1.58, 1.59, 1.60
Mixtures of monochlorbenzene and monochlornaphthalene	1.61, 1.62
Monochlornaphthalene	1.63
Mixtures of monochlornaphthalene and monobromnaphthalene	1.64, 1.65
Mixtures of monobromnaphthalene and methylene iodide	1.66, 1.67, 1.68, 1.69, 1.70
Methylene iodide	1.74

As a general embedding medium in the soil work it will be found convenient to have an oil for the ordinary ray of quartz, as mentioned previously, with an index of 1.545; also one with an index of 1.525 for orthoclase.

OBSERVATIONS ON THE MINERALOGICAL COMPOSITION OF SOILS.

As an illustration of the application of the foregoing methods, the following mineralogical analyses are included. In the interpretation of these analyses it must be borne in mind that they by no means represent the complete soil. Only the sand and silt separates have been examined, the clay separate being discarded in each case. Often the clay is the predominant mechanical constituent, and in these cases possibly only the less dominant materials are recognized. The clay separates are excluded because the exceedingly small size of the grains has so far prohibited their satisfactory identification. Thus the analyses can not be considered as representative of the complete soil; but they do give a general idea of the soil constituents. It is extremely probable from *a priori* reasoning and chemical analyses that the clays are much richer mineralogically than are the separates of larger dimensions. It is unthinkable that the clays should not contain all of the minerals that occur in larger sizes in the sand and silt separates. Ordinary attrition would tend to break up and abrade these minerals, and the finer material would, of course, go into the clays. In addition to these, it is pretty well established that ordinary clays contain a high percentage of kaolin. Chemical analyses lead us to believe that clays are exceedingly rich in their component mineral species.

Ten samples of each type were chosen to get a composite for examination, in order that local characteristics might be avoided. These were all surface soils taken to a depth of 12 inches, and were chosen from the collection of the Bureau of Soils by Dr. George N. Coffey, a field man of wide soil experience. The samples are from cultivated soils and include soils from (a) Arid regions, (b) Crystalline rocks of the Piedmont Plateau, (c) Sandstones and shales, (d) Limestones, (e) Atlantic Coastal Plains, (f) Glacial areas, and (g) Loessal areas.

The mineral composition of the fine sand and silt of these soils is shown in Tables VI and VII; also the minerals which, because of their predominance characterize the soil and those which are less abundant or accessory. Any characteristic feature of the soil or its minerals is described under the heading "Remarks."

SOILS FROM ARID REGIONS.[1]

The soils selected from the arid regions belong in the Fresno, Yakima, and the San Joaquin series. The Fresno soils are light gray in color and are formed from old alluvial fan deposits laid down on the floor of the great Interior Valley of California. The subsoil is separated from the soils by carbonate hardpan. The material is mainly of granitic origin, but is in part derived from volcanic and sedimentary rocks.

The Yakima series consist of ancient lake sediments, with an admixture of volcanic dust or of materials from residual soils of fine texture. They have been derived mainly from basaltic, andesitic or granitic rocks, and occupy mountain footslopes, elevated plateaus, or rolling hills. A thin layer of adobelike structure sometimes occurs in subsoils.

The San Joaquin soils are red, frequently gravelly, consisting of well-worn quartzose material. They are underlain at a depth of 2 or 3 feet by an iron hardpan. These soils are derived from deposits of Pleistocene age, occurring in the Interior Valley of California.

SOILS FROM CRYSTALLINE ROCKS OF THE PIEDMONT PLATEAU AND APPALACHIAN MOUNTAINS.

The Cecil series, the most important and widely distributed of the Piedmont Plateau, includes types with red to gray soils and red clay subsoils. They are of residual origin derived from the degradation of igneous and metamorphic rocks which have weathered generally to great depths.

The Chester series occurs only in the northern part of the Piedmont Plateau and the types differ from the Cecil in having yellow or only slightly reddish subsoils and gray or brown soils. They are much more micaceous and even more subject to erosion than the soils of the Cecil series.

The Iredell series are extensively developed in Virginia and Carolina, forming heavy soil types with a waxy impervious subsoil. They are derived from basic igneous and metamorphic rocks.

The Porters series includes certain residual soils of the Appalachian Mountains derived from igneous and metamorphic rocks. They are analagous to those of the Cecil series, but are classed separately on account of their occurrence on mountain slopes.

SOILS DERIVED FROM SANDSTONES AND SHALES.

The Penn series includes types with purplish-red soils derived from the weathering of red sandstones and shales of the Triassic formation.

The Dekalb series is derived from the disintegration of sandstones

[1] Detailed descriptions of the several soils used in this investigation will be found in Bul. No. 55, Bureau of Soils, U. S. Dept. Agr.

and shales from Silurian to Carboniferous in age. These soils are generally not very productive.

The Morton series includes soils derived principally from the sandstones and shales of the Laramie formation. The soils are brown in color, owing to the accumulation of considerable organic matter. These soils are formed in a region of low rainfall.

SOILS DERIVED FROM LIMESTONES.

The soils of the Hagerstown series are derived mainly from pure massive limestone of Cambro-Silurian age. They occur in lowland areas and belts bordered by areas of more resistant sandstones and shales.

The Clarkesville series is derived largely from the cherty limestones of the St. Louis group of the Lower Carboniferous.

The Decatur soils have an agricultural value intermediate between the Hagerstown and the Clarksville series. They are reddish-brown to red soils with deep red subsoils. They are derived from rather pure hard limestones and occur mainly in the valleys of East Tennessee and Alabama.

ATLANTIC COASTAL PLAIN SOILS.

Four series of soils occurring in the Atlantic Coastal Plains were examined.

The Sassafras soils are yellowish brown in color and have been derived from marine and estuary deposits composed of material from the Piedmont Plateau and limestone valleys mingled with glacial material brought down by large rivers. These types occur in distinct terraces from 10 to 250 feet above sea level in the Coastal Plain around Chesapeake Bay and northward.

The Norfolk series consists of light-colored sandy soils with yellow or orange colored sand or sandy clay subsoils. It occurs in large areas in the South Atlantic Coastal Plain.

The soils of the Greenville series are reddish brown in color, with rather deep red sandy clay subsoils. They occur in the inland part of the Coastal Plain and extend from South Carolina to Texas. They are good cotton soils.

The soils of the Elkton series have light-gray to white surface soils and yellow subsoils. A gravelly subsoil $2\frac{1}{2}$ to 3 feet below the surface is usually saturated with water. They are closely related to the Sassafras soils from which they have been altered by alternate wetting and drying.

GLACIAL SOILS.

The soils of the Volusia series result from the feeble glaciation of the shales and sandstones of the Devonian and Upper Carboniferous rocks of eastern Ohio, southern New York, and northern Pennsylvania. The underlying shales and sandstones have given rise to a large proportion of the soil material, which has been modified to a varying degree by glacial material brought in from other regions. This type occupies rolling hills divided by deep valleys.

The Miami series is one of the most important and widely distributed soil series yet established. The types are characterized by light color of the surface soils. They are derived entirely from glacial material.

The Carrington soils are silty in character, and when wet are more or less sticky and plastic. The series is glacial in origin. The soils are black, and the most extensive type is one of the best grain soils in the country.

LOESSIAL SOILS.

The Marshall series includes the dark-colored upland loessial soils which cover the great prairie region of the Central West. They are distinguished from the Miami by the large quantity of organic matter in the surface soil. They are ranked among the best of our general farming soils. They are closely related to the Carrington soils.

The soils of the Memphis series are brown to gray in color, usually silty in texture, and rest upon silty subsoils. They are derived from the deposit of loess which borders the Mississippi River south of the mouth of the Ohio.

The soils of the Marion series occupy a large proportion of southern Illinois and have a hard silty clay subsoil locally known as hardpan. They are only moderately productive.

TABLE VI.—*Mineralogical analyses of important soils.*

ARID SOILS.

Soil series.	Minerals other than quartz in—		Abundant and characteristic minerals in—		Less abundant or accessory minerals in—		Remarks.
	Sand.	Silt.	Sand.	Silt.	Sand.	Silt.	
	Per cent.	*Per cent.*					
Fresno	30–50	50–70	Hornblende, feldspar, orthoclase, plagioclase,[1] albite to andesine.	Biotite, hornblende...	Epidote, biotite, zircon.	Plagioclase, muscovite, pyroxene, epidote, tourmaline, orthoclase, apatite, zircon.	Mineral grains distinctly angular, characterized by high content of feldspar, mostly alkalic type and generally unaltered. Plagioclase weathered. Traces of diatoms in the silt.
Yakima	50	[2] 50	Augite, volcanic glass, plagioclase, mostly andesine, and labradorite, oligoclase.	Biotite, hornblende, pyroxene, muscovite, diatoms.	Epidote, biotite, phlogopite, apatite, iddingsite, hypersthene, orthoclase.	Plagioclase, orthoclase, apatite, epidote, iddingsite (serpentine).	Grains fairly well rounded to angular. Volcanic glass has inclusions of microlites and trichites. Some feldspars zonally developed. Much devitrified glass.
San Joaquin	20–25	15–20	Hornblende, plagioclase, albite, oligoclase, and andesine, orthoclase.	Biotite, epidote.....	Epidote, zircon, titanite, microcline, biotite, basaltic, hornblende, muscovite.	Muscovite, orthoclase, hornblende, chlorite, tourmaline, zircon, rutile.	Characterized by large amount of hornblende and presence of acid plagioclase. Quartz grains well rounded.

[1] Plagioclase is so listed when the variety could not be determined and in some cases the feldspars could only be listed as such or simply as feldspar residues.

SOILS FROM CRYSTALLINE ROCKS.

Cecil	3–5	10	Zircon, sillimanite, rutile, microcline, plagioclase, biotite.	Sillimanite, chlorite, muscovite, orthoclase.	Epidote, muscovite...	Garnet, hornblende, epidote, tourmaline.	Stretched and undulatory quartzes. Grains most subangular.
Chester	25	30	Hornblende, biotite.....	Hornblende, biotite, muscovite.	Microcline, andesine, tourmaline, magnetite, garnet, chlorite, actinolite, rutile, epidote, muscovite, sillimanite.	Epidote, tourmaline, sillimanite.	Magnetite inclosing rutile needles. Characterized by high content of mica.
Louisa	1–2	5–8	.....	Muscovite (sericite), epidote, sillimanite.	Epidote, zircon, tourmaline, biotite, hornblende, rutile.	Biotite, tourmaline, zircon, rutile.	Grains mostly angular, some rounded, zircons well-rounded. Grains carry inclusions showing secondary origin.

TABLE VI.—*Mineralogical analyses of important soils*—Continued.

SOILS FROM CRYSTALLINE ROCKS—Continued.

Soil series.	Minerals other than quartz in—		Abundant and characteristic minerals in—		Less abundant or accessory minerals in—		Remarks.
	Sand.	Silt.	Sand.	Silt.	Sand.	Silt.	
	Per cent.	*Per cent.*					
Iredell	30+	[1] 40	Pyroxene, augite, hornblende, epidote.	Pyroxene, biotite, epidote, hornblende.	Orthoclase, microcline, andesine, labradorite, apatite, ilmenite, biotite, magnetite.	Hornblende, chlorite, magnetite.	Grains mostly angular, sharply so. Characterized by high percentage of femics.
Porters	13	25–30	Hornblende, orthoclase, microcline.	Biotite, hornblende, muscovite.	Muscovite, biotite, garnet, epidote.	Pyroxene, epidote, zircon, chlorite, plagioclase, microcline, rutile.	Angular grains. A few well-rounded. Minerals show but slight alteration.
SOILS FROM SANDSTONES AND SHALES.							
Penn	5	20	Orthoclase (much altered), hematite.	Decomposed feldspar, epidote.	Epidote, microcline, muscovite, chlorite.	Plagioclase, pyroxene, zircon, biotite, sillimanite, tourmaline, muscovite, magnetite, chlorite.	Many secondary quartz grains inclosing iron oxide. Hematite as inclusions and as a covering of the silt grains.
Dekalb	2–3	8	Orthoclase (very much altered).	Tourmaline	Microcline, zircon, chlorite.	Chlorite, hornblende, muscovite, biotite, epidote, rutile, zircon.	Grains fairly well rounded. Quartz crystals. In the silt the quartz crystals inclose calcite.
Morton	25+	30+	Calcite, orthoclase, feldspar (abundant and altered).	Epidote, hornblende, calcite, orthoclase (altered and fresh).	Microcline, plagioclase, oligoclase, epidote, chlorite, hornblende, tourmaline, apatite, zircon.	Tourmaline, muscovite, apatite, zircon, biotite, chlorite.	Feldspar altered and much rounded, also angular and fresh, suggesting admixture.
Summit	50–60	[1] 60	Plagioclase, oligoclase, labradorite, microcline, orthoclase.	Epidote, hornblende, feldspars, orthoclase.	Apatite, epidote, garnet, pyroxene, zircon, fluorite.	Rutile, chlorite, muscovite, tourmaline, biotite, zircon, sillimanite.	Quartz grains not much worn. Primary and secondary about equal. High feldspar content. Much organic in silt.

SOILS FROM LIMESTONE.

Hagerstown	5–8	8–10	Secondary quartz crystals, microcline, weathered orthoclase.	Altered feldspar	Tourmaline, zircon, chlorite, muscovite, rutile, fluorite.	Hornblende, muscovite, epidote, tourmaline, chlorite, rutile, zircon, microcline.	Angular grains predominate. Quartz grains mostly secondary; rather unusual amount of feldspar.
Clarksville	2–3	2– 5	Secondary quartz crystals, feldspars highly altered.		Tourmaline, rutile, zircon, hornblende, garnet, chlorite, biotite (partly altered to chlorite).	Tourmaline, muscovite, epidote, chlorite, zircon, hornblende, microcline.	Many of the quartz grains fairly well rounded, others angular.
Decatur	[1] 4	5– 7	Many secondary quartz crystals carrying inclusions of calcite.		Tourmaline, zircon, rutile.	Tourmaline, muscovite, biotite, rutile, hornblende, zircon.	Angular, subangular, to well-rounded grains 2:1:1. Characterized by abundant quartz crystals. Quartz grains in the silt carry calcite.

COASTAL PLAIN SOILS.

Sassafras	12	18–20		Biotite, hornblende	Hornblende, biotite, muscovite, apatite, chlorite, microcline, epidote, rutile, tourmaline, hypersthene, weathered orthoclase.	Muscovite, orthoclase, epidote, acid plagioclase, microcline, staurolite, zircon, tourmaline.	Angular grains predominate 2 : 1. Complex mixture of varied mineralogical composition.
Norfolk	1 or less.	3– 5			Microcline, apatite, zircon, tourmaline.	Microcline, orthoclase (altered), biotite, chlorite, hornblende, zircon, tourmaline, rutile, sillimanite, epidote.	Well-rounded quartz grains, also zircons. Many quartz grains secondary carrying inclusions of iron oxide.
Greenville	3–5	5– 8	Feldspar residues		Magnetite, apatite, zircon, rutile, sillimanite, weathered feldspar.	Biotite, epidote, chlorite, rutile, zircon, blue magnetite, sillimanite, tourmaline.	Quartz and zircon well rounded. Many secondary quartz grains inclosing iron oxide.
Elkton	3	3			Rutile, tourmaline, chlorite, microcline, zircon, magnetite.	Muscovite, orthoclase, microcline, hornblende, rutile, epidote.	Admixture of angular and well-rounded grains 1:1. Many sponge spicules are present, indicating swampy conditions. Secondary quartz grains subordinate.

[1] Estimated.

TABLE VI.—*Mineralogical analyses of important soils*—Continued.

GLACIAL SOILS.

Soil series.	Minerals other than quartz in—		Abundant and characteristic minerals in—		Less abundant or accessory minerals in—		Remarks.
	Sand.	Silt.	Sand.	Silt.	Sand.	Silt.	
	Per cent.	*Per cent.*					
Volusia	10–12	8–10	Microcline, orthoclase (very much altered and fresh).	Feldspar residue	Garnet, zircon, chlorite, biotite, hornblende, tourmaline, epidote, albite.	Chlorite, biotite, hornblende, epidote, muscovite, tourmaline.	Grains well rounded; many secondary quartz grains. Orthoclase altered to epidote. Admixture of fresh orthoclase. Silt shows extensive chemical alteration.
Miami	10	10–15	Hornblende, garnet, microcline.		Orthoclase, zircon, epidote, oligoclase, apatite, garnet.	Tourmaline, hornblende, epidote, chlorite, orthoclase, microcline, zircon.	Well-rounded grains.
Carrington	15	20	Hornblende, epidote, garnet, magnetite, ilmenite, microcline, feldspars in some quantity.	Hornblende, chlorite	Hornblende, chlorite, zircon, plagioclase, albite, oligoclase.	Epidote, biotite, calcite, rutile, muscovite, plagioclase, orthoclase.	Rounded to angular grains characterized by high feldspar content and high percentage of minerals other than quartz.
SOIL FROM WIND-LAID MATERIALS (LOESS).							
Marshall	12	15–20	Feldspar, including orthoclase, microcline, plagioclase, oligoclase, andesine.	Epidote, muscovite	Apatite, muscovite, hornblende, rutile, garnet, zircon, sillimanite.	Hornblende, biotite, chlorite, tourmaline, orthoclase, zircon, microcline, sillimanite.	Grains mostly angular; a few fairly well rounded. Orthoclase much altered, also fresh orthoclase. A few quartz crystals.
Memphis	15	15	Feldspars, orthoclase (altered), microcline.		Biotite, albite, oligoclase, zircon, fluorite, rutile, tourmaline, apatite, hornblende.	Biotite, hornblende, epidote, muscovite, orthoclase, microcline, sillimanite, rutile, zircon.	Most grains well rounded. A few angular grains.
Marion	10–12	12	Microcline, hornblende, orthoclase.	Orthoclase, hornblende.	Fluorite, zircon, garnet, tourmaline, plagioclase, oligoclase, epidote.	Tourmaline, microcline, epidote, titanite, chlorite.	Admixture of angular and well-rounded grains. Admixtures of altered and fresh orthoclase. Some minerals highly altered; others entirely fresh.

TABLE VII.—*Summary of minerals present in important soil series.*

Mineral.	Number in which found.	Fresno.	Yakima.	San Joaquin.	Cecil.	Porters.	Chester.	Louisa.	Iredell.	Penn.	Dekalb.	Morton.	Summit.	Hagerstown.	Clarksville.	Decatur.	Elkton.	Sassafras.	Norfolk.	Greenville.	Volusia.	Miami.	Carrington.	Marshall.	Memphis.	Marion.
Quartz	25	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C
Hornblende	23	C	C	C	A	C	C	A	C	....	C	C	C	A	A	A	A	C	A	....	A	C	C	A	A	C
Orthoclase	20	C	C	C	A	C	....	....	A	C	A	C	C	C	....	....	A	A	A	....	C	A	C	A	C	C
Microcline	20	....	....	A	C	C	A	....	A	A	A	A	C	A	A	....	A	A	A	....	C	C	C	C	C	A
Epidote	24	A	A	C	A	A	A	C	C	C	A	C	C	A	A	....	A	A	A	A	A	A	C	C	A	A
Biotite	21	C	C	C	C	C	C	A	C	A	A	A	A	....	A	A	....	C	A	A	A	....	A	A	A	....
Muscovite	20	A	C	A	C	C	C	C	....	A	A	A	A	A	A	A	A	A	....	....	A	....	A	C	A	....
Zircon	22	A	....	A	C	A	....	A	....	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Chlorite	21	....	A	A	C	A	A	....	A	A	A	A	A	A	A	....	A	A	A	A	A	A	C	A	....	A
Tourmaline	21	A	....	A	A	....	A	A	....	A	C	A	A	A	A	A	A	A	A	A	A	A	....	A	A	A
Rutile	17	....	....	A	....	A	A	A	....	....	A	....	A	A	A	A	A	A	A	....	....	....	A	A	A	A
Plagioclase	13	C	C	C	....	A	....	....	A	A	....	A	C	....	....	....	....	A	....	....	....	A	A	C	....	A
Apatite	12	A	A	....	....	....	....	....	A	....	....	A	A	....	....	....	....	A	A	A	....	A	....	A	A	A
Garnet	10	....	....	....	A	A	A	....	....	....	....	....	A	A	....	....	....	....	....	A	A	A	C	C	....	....
Sillimanite	10	....	....	....	C	....	A	C	....	A	....	....	A	....	....	....	....	....	A	A	....	....	....	A	A	A
Oligoclase	7	....	....	C	....	....	....	....	....	....	....	A	C	....	....	....	....	....	....	....	....	A	A	C	A	....
Andesine	6	C	C	C	A	....	....	....	A	....	....	....	....	....	....	....	....	....	....	....	....	....	....	C	....	....
Albite	5	C	....	C	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	A	....	A	....	A	....
Pyroxene	6	A	C	....	....	A	....	....	C	A	....	....	A	....	....	....	....	....	....	....	....	....	....	....	....	....
Magnetite	6	....	....	....	....	....	A	....	A	A	....	....	....	....	....	....	A	....	....	A	....	....	C	....	....	....
Labradorite	3	....	C	....	....	....	....	....	A	....	....	....	C	....	....	....	....	....	....	....	....	....	....	....	....	....
Titanite	2	....	....	A	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	A
Fluorite	4	....	....	....	....	....	....	....	....	....	....	....	A	A	....	....	....	....	....	....	....	....	....	....	A	A
Augite	2	....	C	....	....	....	....	....	C	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Ilmenite	2	....	....	....	....	....	....	....	A	....	....	....	....	....	....	....	....	....	....	....	....	....	C	....	....	....
Calcite	2	....	....	....	....	....	....	....	....	....	....	C	....	....	....	....	....	....	....	....	....	....	A	....	....	....
Hypersthene	2	....	A	....	....	....	....	....	....	....	....	....	....	....	....	....	....	A	....	....	....	....	....	....	....	....
Sericite	1	....	....	....	....	....	....	C	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Phlogopite	1	....	A	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Hematite	1	....	....	....	....	....	....	....	....	C	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Serpentine	1	....	A	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Actinolite	1	....	....	....	....	....	A	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Iddingsite	1	....	A	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....
Staurolite	1	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	....	A	....	....	....	....	....	....	....	....
Number of minerals	.....	13	17	16	13	13	13	10	15	14	11	14	19	12	10	7	11	15	12	11	12	12	17	17	15	14

C=abundant. A=accessory.

DISCUSSION OF RESULTS.

From the summary of the examination of these soils it will be seen that soils have a greater variety of minerals than found in ordinary igneous or metamorphic rocks. It is true that the samples examined were composite in nature, and one would therefore expect a more complex constitution than in case of a sample from a single boring. But experience has shown that this complexity of mineral composition is a peculiarity of soils, and this character is believed to be due to their unconsolidated nature which permits thorough mixing.

The alkali feldspars are among the most abundant of the common rock-forming minerals found in soils. Orthoclase may be very much altered, as in soils derived from secondary rocks, or, on the other hand, quite fresh, as in soils of more recent origin, such as glacial types. Microcline occurs always in bright unaltered cleavage fragments which show no signs of chemical alteration. The persistence of microcline is noteworthy, as it occurs in the leached and water-worn sands comprising the Norfolk series of the Atlantic Coastal Plain. These soils are predominantly quartz with an admixture of microcline, zircon, tourmaline, rutile, and occasionally hornblende. Feldspar grains are frequently so deeply altered that only a mere shell or skeleton of the original mineral appears. The larger feldspar fragments found in the sand separates are purer than those occurring in the silt. In some samples the only trace of feldspar in the silt is in the so-called feldspar residues, short, needlelike particles that possess an index of refraction close to that of pyrophyllite. The feldspar content of the silt is much higher than that of the sand, but the silt particles are not as pure. Microcline occurs in the silt as fresh unaltered particles, too small at times to show the twinning bands. These particles, having the same index as orthoclase, are distinguished from the latter by the high extinction angle (15°), measured from the traces of the cleavage which are nearly always present in microcline. In the same soils unaltered feldspar fragments will be found together with deeply altered grains. Upon investigating several of these soils it was found that this is due to local conditions where there has been an admixture of soils. In several Norfolk soils quantities of unaltered feldspar fragments were found mingled with others much altered. A granite exposure 12 miles away is supposed to have supplied the material.

The intermixing of minerals is quite evident in glacial soil types, less so in other types, but is present to some extent in most soils. This admixture of grains may be due in part to the movement of the soil particles under the influence of frost or water circulation, the effect of which would be to raise particles of the subsoil or the partly decomposed rock mass. The acid members of the plagioclase series,

albite and oligoclase, appear generally in rather fresh grains. The more basic members, however, are deeply altered, so much so that at times their identification has not been possible. In the soil from arid regions the more basic members of the series are quite fresh, and frequently show traces of the banded or zonal development. Cleavage fragments of microcline showing only pericline twinning are similar in appearance to the more basic plagioclases, which possess broad twinning bands. Cleavage fragments of microcline showing only the pericline twinning are readily distinguished from plagioclase, which possess broad twinning bands by the combination of low index with higher extinction angle (15°) of these twins and the trace of the (001) cleavage normal to the twinning lines, also by the fresh appearance of the microcline.

The predominance of hornblende and epidote as soil minerals is evident from the summary of the examinations. These minerals have been found in practically all soils and in abundant quantities. They are found in both the sand and silt separates, being particularly abundant in the former. Hornblende at times shows a tendency to alter into chlorite. Epidote, however, generally exists in bright yellow grains showing little or no chemical alteration. Yellow spores at times occur in soils, and because of their relief (due to low index) have a somewhat similar appearance to epidote. These can be distinguished easily by the Schroeder Van der Kolk method. The micas are persistent minerals in soils and show but little evidence of alteration, a "fraying" of the edges at times being quite characteristic. If alteration of the micas has taken place it has not influenced their optical properties. It would appear that micas are the most stable of the potash minerals found in soils, excepting microcline. This observation is in line with the experiments of Johnstone, who found very little alteration of the micas after a year's suspension in carbonated water.[1]

Tourmaline, rutile, and zircon are practically always present in minute quantities in soils, as the concentrates from rock degradation. These are hard insoluble minerals and resist the forces of chemical and physical disintegration. They occur more often as crystals with prismatic elongation, sometimes with edges quite rounded, as in the Norfolk soils. Rutile and zircon are found principally in acid igneous rocks, and from their presence in most soils it would apparently indicate that these soils had been derived in part at least from these rock types, indicating thereby the mixing of soil materials.

Apatite has been identified in one-half of the soils examined, being invariably the fluor-apatite (index = 1.63). This is a striking fact, indicating that this mineral is much more resistant to chemical solution than its chlor analogue.

[1] Quoted from Merrill.

Garnet has been identified in 10 samples, usually in rounded grains of a light-pink color and high index. In the silt particles the color is entirely lacking. It seems to be a fairly resistant mineral, occurring both in the sand and silt separates as clear grains. It is found as a characteristic feature of two of the glacial soils and as an accessory mineral in soils from the Piedmont section and in some of the soils of the Atlantic Coastal Plain. It will be remembered that garnets are found in the Precambrian schists, which make up a great portion of the rocks of the Piedmont section, from which some of these soils have been derived.

Pyroxene does not appear frequently as a soil-forming mineral. Considering its importance and abundance in igneous rocks it is rather an exceptional mineral in soils. Its place is more or less taken by epidote and hornblende, into which it alters, as is shown in petrographic examination. Augite is abundant in the Yakima and the Iredell soils, soils which have been derived from basic pyroxene rocks.

Chlorite is a constant soil-forming mineral. It seems to be the final alteration product of the ferromagnesian minerals, with iron set free as oxide and the magnesium with silica and alumina forming chlorites.

The iron ores, magnetite and ilmenite, occur in subordinate amounts in a few soils. Magnetite seems to alter to the hydrated sesquioxide of iron. This alteration appears to be influenced by slight differences in chemical composition. The magnetic particles may be deeply covered with the red iron oxide and, at times, do not even show a black center of unaltered magnetite. In the same soil black magnetic particles will occur with not even a trace of the red oxide on the surface. A chemical examination of these particles on account of the very small quantity available was not entirely satisfactory in explaining these differences. The red magnetic particles were found to contain 3 per cent magnesium oxide.

Calcite has not been found to any extent in soils of the provinces of free rainfall. It sometimes is present inclosed in quartz crystals and at times in arid regions inclosed in gypsum. Even the surface soils of the series derived from limestones are practically free from calcite. This no doubt is due to the effect of the decomposing organic matter producing carbon dioxide, which has been active in leaching the calcite from the soil.

Quartz is the most abundant of the soil-forming minerals. It constitutes up to 99 per cent or more of some sandy soils; the silt separate is also predominantly quartz. In some soils there is evidence that the quartz particles have been enlarged secondarily, and these grains carry inclusions of clay and iron oxide. These grains are generally seen in soils derived from sedimentary rocks. The primary character of quartz particles is recognized in the Norfolk and Sassafras

soils. The grains here are generally clear and transparent and frequently carry inclusions of apatite, rutile, zircon, and other minerals, also of gas vesicles and in a few cases of liquid bubbles.

The undulatory extinction of minerals which have been under strain is preserved in many of the quartz grains in the soil. These grains are generally from metamorphic rocks and their origin or modification is indicated by their undulatory extinction, also by the stretched appearances first noted by Sorby. The physical appearance of the quartz particles has a certain diagnostic value in ascertaining the geological forces which have been active in the formation of the soil. The well-rounded quartz grain suggests a rolling about as unconsolidated material exposed to disintegrating geological forces under whose influence many of the other minerals have disappeared. Fresh angular grains, on the other hand, suggest material of more recent origin from igneous or metamorphic rocks or material which has not been transported.

Soils which have previously existed as swamp or as the beds of ponds or lakes contain siliceous remains of sponges and other low orders of plant life. These are the so-called phytolitharien of Steinriede. These siliceous spicules may be easily mistaken for fluorite on account of their low index of refraction (opal). The presence of this phytolitharien is indicative of low swampy grounds or ponds. Such conditions have evidently existed in the case of the Elkton soils and has resulted in the changing of material similar to the Sassafras soils over into soils of much lower mineral content and lower agricultural value. The effect of this swampy condition and of the alternate wetting and drying has been to dissolve the minerals. In a few soils from Georgia and other Southern States the accumulation of sponge spicules is enough to cause injury to the feet of laborers and work stock.

From the mineralogical composition of soils it would seem that the processes of soil and rock weathering tend to leach out the alkalies and the alkali earths, to separate iron as oxide, and to form quartz and insoluble magnesium and aluminum silicates. The organic matter of the soil assists in the reduction of the iron oxide formed, thereby favoring its transportation in the soil water which is more or less charged with carbon dioxide.

In these examinations kaolinite and limonite, the common products of mineral decay, are not listed. These minerals, on account of their fine division are carried into the clay separate in the mechanical preparation necessary to this method of examination. They make up the greater portion of the clay separates, the relative proportion of the two varying.

The mineralogical composition of soils is found to vary with the physiographic region in which they occur. Thus the percentage of minerals other than quartz in the soils from the semiarid regions of the

West is found to be quite high and the minerals generally appear as well preserved grains. They show evidence of mechanical attrition but the chemical decomposition has not affected the minerals to any extent. The percentage of minerals other than quartz in the soils of the Atlantic Coastal Plain varies somewhat. These soils are from the reworked material of the Piedmont Plateau and are much poorer in mineral content than the soils from the latter province, except in the case of the Sassafras soils, which occupy the northernmost part of the Coastal Plain, and which probably contain admixtures of glacial material brought down by the rivers which traverse this area. The Elkton soils have been derived from the same material as the Sassafras, but have been much modified by lying in low places exposed to swampy conditions. The mineral content of these soils has been lowered; their productivity is also much lower than that of the Sassafras series. The soils of the Piedmont Province have been derived from igneous and metamorphic rocks and have a higher content of minerals than the soils of the Coastal Plain. The high content of muscovite and biotite and the presence of garnet and sillimanite in these soils is noteworthy. These minerals are developed in metamorphic rocks and their presence in soil is indicative of the origin of the soil material. These soils lie in a region of relatively heavy rainfall and their content of minerals, other than quartz, is not nearly so large as in case of soils in less humid regions. The Porters series is an Appalachian Province series and shows a greater content of minerals, with angular grains and little chemical alteration, than the Piedmont series. The Porters is the Appalachian counterpart of the Cecil in source of material and such differences as occur are due entirely to differences in physiographic position, the Porters series lying at higher elevations in the mountains. In case of the Chester soils it is probable that the magnetite-carrying rutile crystals are derived from the Chickie quartzite, the Cambrian sandstone of the Piedmont Plateau. This formation contains a hard, black ilmenite, so-called. The author has examined this ilmenite independently at the suggestion of Prof. Withrow, of Ohio State University, and finds that it contains abundant inclusions of rutile crystals, some twinned. These crystals range from the tiniest needles to grains 0.1 millimeter in length. The black mineral is probably hematite. The Iredell soils are derived from basic igneous rocks, which fact is revealed by the high content of ferric minerals.

Soils derived from sandstones and shales show especially the effect of climatic conditions. Those from regions of high rainfall, the Penn and the Dekalb soils, have a low percentage of minerals other than quartz. The minerals themselves are deeply altered. On the other hand, soils derived from sandstones and shales in regions of low rainfall, as the Morton and Summit series, have a much higher mineral

content and the minerals are much less altered. The minerals of the Summit soils are better preserved than those of the Morton but the quartz grains of the latter are well rounded, indicating a rolling about as unconsolidated material exposed to geological agencies.

Soils derived from limestones show a rather low content of minerals other than quartz in the sand and silt separates. These soils are characterized by the presence of quartz crystals with pyramidal termination, often carrying calcite inclusions. They probably have been formed in cavities or cracks in the original limestone. The other minerals are rather deeply altered and their nature suggests the admixture of other soils or rock material. Feldspars have been found in crystalline limestones, but it is not likely that the feldspars in these soils were native to the limestone. Limestone soils generally occupy valleys and are favorably situated for the accumulation, by wash, of materials derived from other rocks.

The glacial and loessial soils are heterogeneous mixtures of varying mineral composition. Differences in the shape of the quartz grains and in the condition of alteration of the feldspar particles indicate a mixing of material of diverse origin. The mineral content is fairly varied, but in the case of the loessial soils the minerals are deeply altered. A coating of calcium carbonate is sometimes found on particles in loessial soils, though not in any of the series examined. A similar coating has been observed on wind-blown materials.

DESCRIPTION OF SOIL-FORMING MINERALS.

FELDSPARS.

The Feldspars, the most important rock-forming minerals, are very abundant and widely distributed. They are the basis for the classification of igneous rocks and have a very important bearing upon soil mineralogy.

The feldspars are characterized by two highly developed cleavages, one parallel to the face (001) and the other to the face (010).

Chemically they are alumino-silicates of potash, soda, and lime, more rarely of barium. This chemical composition of the feldspars permits a ready separation of the group into the potash feldspars and the plagioclases or lime-soda feldspars. The potash feldspars are divided into the monoclinic variety orthoclase, chemical formula $KAlSi_3O_8$ and the triclinic potash feldspar, microcline. The latter differs megascopically from orthoclase in that the angle between the direction is 89° 30′ instead of 90° in the monoclinic minerals.

Orthoclase is the feldspar which forms the predominant mineral in granites and their effusive equivalents. It appears in rocks frequently twinned after the Carlsbad law. This twining is occasionally seen in soil grains. It is easily recognized between crossed nicols and also by the different orientation of the two individuals,

which is revealed by the use of a selenite plate. The extinction on the face (001) is parallel and on the face (010) equals 5°–6°.

Orthoclase may be recognized by the peculiar alteration product formed from it.

Microcline is a very persistant mineral in soils. It is characterized by polysynthetic twinning after the albite and pericline law. The albite twinning face is parallel to (010) and the pericline twinning occurs in the zone parallel to the (100). The (001) cleavage face shows the peculiar lattice work or plaid effect (between crossed nicols) showing both the albite and pericline twinning. The extinction angle of these twins = 15.5°. The (010) face shows only the pericline twinning which is almost normal to the trace of 001 cleavage and has positive elongation.

Microcline occurs in granites, gneisses and certain metamorphic rocks. It is readily distinguished — on (010) face — from plagioclases by low indices and high extinction angle, also by the absence of alteration in the former. Microcline on the (010) face shows well-developed cleavage normal to the twinning plane, distinguishing it from plagioclase, whose cleavage direction on (001) face is parallel to twinning plane. Microcline on (010) face shows pericline twinning and may be confused with acid plagioclase showing albite twinning.

The plagioclases or soda calcic feldspars vary in chemical composition from a pure soda feldspar albite $NaAlSi_3O_8$ to the pure or nearly pure calcic feldspar, Anorthite. $CaAl_2Si_2O_8$, the chemical composition of the plagioclase separating from the molten magma varies as the composition of the magma varied. In certain crystals of plagioclase in rocks there was a change in composition as the crystal grew, owing to changes in concentration of the magma.

These changes in composition may be clearly seen to be progressive changes by observation in polarized light. The minerals have grown by adding shell after shell of different chemical composition.

In general then the composition of the feldspars composing igneous rocks will vary. In the nature of the case the igneous rocks rich in silica will be composed of the series near albite. With a difference in chemical composition the plagioclases offer differences in physical properties, particularly optical properties. There have been designated the following members of the plagioclase group: Albite, oligoclase, andesine, labradorite, bytownite, and anorthite.

As the series decreases in silica content the resistance of these minerals to the atmospheric agencies of weathering also decreases. In fact, albite is a secondary mineral and is formed in nature by weathering.

The plagioclases are characterized by polysynthetic twinning after the Albite law. This twinning is shown on the cleavage face (001) and in the zone of symmetry. The extinction of these twins on the

(001) face is shown in Table VIII; also the variation in the indices of refraction.

The extinction of the twins, however, in the zone parallel to the face (010) varies so that unless the feldspar is a cleavage fragment it may be unsafe to use the extinction angle of the albite twins as a diagnostic. The variation in the extinction angle of the series between Ab and Ab_7 An_3 is very little. The larger extinction angles in this zone are characteristic of plagioclases more basic than andesine. In general, the wider the individuals, the more basic the plagioclase. Fine twinning is more apt to be present in the acid series.

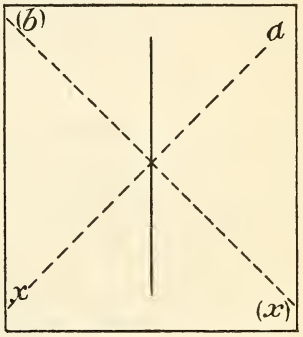


FIG. 12.—Relation between extinction angles and crystallographic direction.

The orientation of the plagioclases varies as shown by the extinction angles on the faces (001) and (010), from the trace of the other cleavages. The (010) face at times shows pericline twinning (very fine lines), also a parting parallel to the face (001).[1]

The change in index of refraction of the feldspars with the change in chemical composition furnishes the soil mineralogist with a much easier and more certain method of identification than that afforded by the use of extinction angles. For identification of the feldspars by differences in extinction of the Carlsbad and albite twins and for other means of distinguishing this important group of minerals the student is referred to Rosenbusch Iddings, Johannsen, or Winchell.

TABLE VIII.—*Physical properties of the feldspars.*

Feldspar.	Specific gravity.	Optical character.	Extinction angle on (001).	Extinction on face (010).	Indices. α	Indices. β	Indices. γ	Composition.
			° ′	° ′				
Anorthite	2.765	—	—36 30	—36	1.575	1.583	1.588	1:6–0:1
Bytownite	2.725	—	—17 40	—29 28	1.561	1.564	1.569	1:3–1:6
Labradorite	2.696	+	— 5 30	—16	1.555	1.558	1.563	1:1–1:2
Andesine	2.675	+	— 2 30	— 7 58	1.549	1.553	1.556	3:2–4:3
Oligoclase	2.645	—	+ 2	+ 4 36	1.539	1.543	1.546	6:1–2:1
Albite	2.610	+	+ 4	+19 30	1.529	1.533	1.539	1:0–8:1
Microcline	2.57	—	15 30	5–6	1.522	1.526	1.529	Or.
Orthoclase	2.56	—	0	5–6	1.518	1.522	1.524	Or.

OPAQUE MINERALS.

Magnetite.—Magnetite crystallizes in the isometric system. The common form is the octahedron, occasionally the dodecahedron; also massive with laminated structure, granular, impalpable. Fracture

[1] Extinction angles are measured as positive or negative from a crystallographic direction as the vibration plane of the mineral is after or before the crystallographic direction. With plagioclase for example a=+30 b=—30°, and all extinction angles are measured from the ellipsoidal axis. (See fig. 12.)

subconchoidal to uneven. Brittle; H. = 5.5–6.5; G = 5.168–5.18. Strongly magnetic, which characteristic affords a method of separating the magnetite from other grains with which it may be associated.

Magnetite is an iron ferrate, Fe_3O_4 or $FeOFe_2O_3$. The ferrous iron is sometimes replaced by magnesium and more rarely by nickel. Occasionally it is titaniferous. Before the blowpipe it is difficultly fusible. In the oxidizing flame it loses its influence on the magnet. It is soluble in hydrochloric acid.

Magnetite is opaque, except in the case of very thin plates included in mica. Thin plates are pale brown to black in transmitted light. Streak, black; luster, metallic and splendent to submetallic and dull.

Magnetite resembles hematite, ilmenite, chromite, and graphite. It may very readily be distinguished from these by its strong magnetism and solubility in acids.

Ilmenite (*menaccanite*).—Ilmenite crystallizes in the rhombohedral division of the hexagonal system. The crystals are usually thick tabular and acute rhombohedral. Often in thin plates. Also massive, compact, and granular. *Fracture* conchoidal. H = 5–6; G = 4.5–5.

$FeTiO_3$ or $(FeTi)_2O_3$. Magnesium replacing the ferrous iron is sometimes present. Slowly dissolves in hydrochloric acid. Infusible in the oxidizing flame, but slightly rounded on the edges in the reducing flame.

This mineral is opaque, except in the case of very thin flakes and microscopic crystals. In the opaque crystals the color is iron black; in very thin flakes, clove-brown. Streak, black, brownish-red. Luster, metallic to submetallic.

Ilmenite resembles hematite and magnetite. These minerals can not always be distinguished. Ilmenite is very resistant to acids and is of a different color from hematite. It is of very much weaker magnetism than magnetite.

Graphite.—Graphite crystallizes in the rhombohedral system. It sometimes is found in 6-sided tabular crystals, but in its more usual form it occurs as irregular flakes. The cleavage is perfect, parallel to the base. Occasionally it is found in granular, compact, or earthy forms. H = 1–2; G = 2.09–2.23. Color is iron black to dark steel gray.

Graphite is carbon, C, but it generally contains iron sesquioxide and clay impurities, besides other substances. It is infusible, but burns at a high temperature. It is unaltered by acids.

Graphite is opaque in even the thinnest flakes. The color is iron black to steel gray, and the luster metallic, dull, or earthy.

Graphite resembles the mineral molybdenite closely. From this it can be distinguished by the fact that molybdenite gives a sulphur

reaction. Magnetite is much harder and does not resist the attack of acids.

Chromite.—Chromite crystallizes in the isometric system, usually in octahedrons. It is also found in massive, granular, and compact states. H = 5.5; G = 4.32–4.57. Sometimes it is feebly magnetic.

Chromite is an iron chromate, $FeCr_2O_4$. Magnesium sometimes replaces part of the iron. Aluminum and ferric iron replace part of the chromium. It is not acted upon by acids.

Chromite is translucent to opaque. The color ranges between iron black and brownish black. Very thin flakes are brown, reddish brown, and yellowish red. The index of refraction = 2.0965. The luster is submetallic to metallic.

Pyrite.—Pyrite crystallizes in the isometric system, usually in the form of pyritohedrons. Cubes and octahedrons are also found. It is also found in massive and granular forms. The fracture is uneven to conchoidal. H = 6.65; G = 4.95 – 5.10. The streak is greenish black to brownish black.

Pyrite is an iron disulphide, FeS_2. Copper, nickel, cobalt, and thallium occasionally replace part of the iron. Gold is sometimes found distributed through the mineral. On burning, it gives the characteristic sulphur odor. Nitric acid decomposes it, but it is insoluble in hydrochloric acid.

Pyrite is opaque. The color is a pale brass yellow. The luster is metallic.

Pyrite resembles chalcopyrite, but lacks the darker color and more brasslike appearance of the latter mineral. It is distinguished from pyrrhotite by the lighter color and lack of magnetic properties, as well as by its behavior toward acids.

Hematite.—Hematite crystallizes in the rhombohedral system. The fracture is uneven to subconchoidal. The compact forms are brittle, but thin laminæ are elastic. H = 5.5 – 6.5; G = 4.9 – 5.3. Sometimes it is feebly magnetic. There are several varieties of hematite, as follows: Specular or micaceous hematite; compact hematite; red ocherous hematite, which are more or less earthy; sand, clay, ironstone, etc.

Hematite is an iron sesquioxide, Fe_2O_3. Titanium and magnesium are sometimes present. It is soluble in concentrated hydrochloric acid.

Hematite has a luster metallic, splendent, and sometimes dull. The color varies from a dark steel gray to an iron black. In the case of very thin flakes, when light can be transmitted, it is blood red. The streak is cherry red or reddish brown. Except in very thin laminæ, it is opaque. It is uniaxial and optically negative (–). The index of refraction varies from 2.94 to 3.22. It is pleochroic in sections perpendicular to the base. It can be distinguished from limonite by its deeper color and crystallization.

Limonite.—Limonite is an amorphous substance. It occurs usually as a coating on the soil grains. H = 5 – 5.5; G = 3.6 – 4.

Limonite is hydrated iron oxide, $2Fe_2O_3.3H_2O$. The common impurities are sand, clay, phosphates, manganese oxides, and organic matter. On heating in a closed tube it gives off water and is converted into red iron sesquioxide. It is soluble in hydrochloric acid.

Limonite is opaque and has a silky or submetallic, or sometimes dull, earthy luster. The color is various shades of dark brown, sometimes black. The earthy varieties are brownish yellow and ocherous yellow. The streak is yellowish brown.

ISOTROPIC MINERALS.

Fluorite.—Fluorite crystallizes in the isometric system. The form is usually cubic, but sometimes octahedral. It is also occasionally massive or granular. The fracture is flat—conchoidal and splintery. Cleavage is octahedral, brittle. H = 4; G = 3.01 – 3.25.

Fluorite is a calcium fluoride, CaF_2. On heating, it phosphoresces and decrepitates. It gives the ordinary calcium flame reaction (red).

The luster is vitreous. The color ranges through white, yellow, green, rose red, crimson red, violet blue, sky blue, brown, wine yellow, and greenish blue. The streak is white. The mineral is usually isotropic, but may be doubly refracting. The index of refraction varies from 1.4336 to 1.4343. It resembles opal, analcite, and sodalite. Its cleavage distinguishes it from analcite and sodalite.

Opal.—Opal is an amphorous substance. It is generally massive. H = 5.5 – 6.5; G = 1.9 – 2.3. The fracture is conchoidal.

Opal is silicon dioxide, silica, SiO_2, plus varying amounts of water. The water varies from approximately 2 to 13 per cent. The impurities consist of quartz, ferric oxide, alumina, lime, magnesia, and alkalies. There are very many varieties of opal, which for soil purposes may be ignored. Heated, it yields water. It is infusible. Is soluble in hydrofluoric acid and the caustic alkalies.

The luster is vitreous, subvitreous, resinous, and pearly. The color is white, yellow, red, brown, green, gray, pale blue. The mineral, especially in the precious varieties, often shows a rich play of colors in refracted and reflected light. The streak is white. It is transparent to nearly opaque. It often shows double refraction due to strains. Mammillary forms, hyalite, often show uniaxial interference figures of a negative character, indicating a shrinkage and radial compression. The index of refraction varies from 1.368 to 1.458.

Opal resembles leucite and sodalite. It can be distinguished from these minerals by its lower refraction.

Sodalite.—Sodalite crystallizes in the isometric system. The common form is the rhombic dodecahedron. It also occurs in massive and granular forms, and in concentric nodules. The cleavage is

dodecahedral. The fracture is conchoidal to uneven. H = 5.5 – 6; G = 2.14 – 2.3.

Sodalite is $Na_4(AlCl)Al_2Si_3O_{12}$. Potassium sometimes replaces part of the sodium. It fuses with intumescence to a colorless glass. Hydrochloric acid decomposes it with the separation of gelatinous silica.

The luster is vitreous or greasy. The color is blue, gray, greenish, yellowish, white, lavender, and light red. The mineral is transparent to translucent. The streak is uncolored. The index of refraction varies little from 1.48. The presence of inclusions sometimes gives rise to a faint double refraction.

Sodalite resembles closely the other members of the sodalite group, These can not well be differentiated except chemically. The presence of chlorine distinguishes sodalite from these other minerals. To test for chlorine, expose the mineral to nitric acid containing silver nitrate. The surface will become clouded with silver chloride if any chlorine is present.

Analcite.—Analcite crystallizes in the isometric system, usually in trapezohedrons. It also occurs as cubes, massive, granular, and concentric structures. The cleavage is cubic. The fracture is subconchoidal. H = 5 – 5.5; G = 2.22 – 2.29.

Analcite is anhydrous metasilicate of sodium and aluminum, $NaAlSi_2O_6 + H_2O$. It yields water in the closed tube. It fuses to a colorless glass and gelatinizes in hydrochloric acid.

The luster is vitreous. The color is white, grayish, greenish, yellowish, reddish white, and colorless. Analcite is transparent to nearly opaque. Owing probably to loss of water it sometimes shows weak double refraction. The index of refraction is 1.4874.

Analcite resembles closely the colorless sodalites, leucite, opal, and colorless rock glass. It has a lower refraction than the glasses. Its cleavage, when present, distinguishes it from opal and leucite. From sodalite it may be distinguished by the presence or absence of chlorine as given under sodalite. Hauynite and noselite contain sulphur while analcite does not. To test for sulphur, subject the crystal to the action of hydrochloric acid in which a little barium chloride is dissolved. If sulphur is present barium sulphate will be precipitated.

Noselite.—Noselite crystallizes in the isometric system, in dodecahedral and granular massive forms.

Noselite is $Na_4(NaSO_4Al)Al_2Si_3O_{12}$. It is *isomorphous* with hauynite, and these two minerals grade imperceptibly into each other. They are also very much alike physically, and sometimes they can not well be differentiated. With hydrochloric acid noselite gelatinizes. The color is sky blue, gray, brownish, red, yellow, green, or colorless. It is usually either blue or colorless. The presence of

inclusions sometimes makes the mineral nearly opaque. It is isotropic, but occasionally shows weak double refraction. The index of refraction is 1.4961.

Noselite can be distinguished from hauynite by the presence of calcium in the former. To test for calcium, decompose the mineral with hydrochloric acid. Allow the gelatinous silica to dry. If calcium is present, crystals of gypsum ($CaSO_4 2H_2O$) will form.

Hauynite.—Hauynite crystallizes in the isometric system. It occurs in dodecahedrons, octahedrons, and rounded grains. The cleaveage is dodecahedral. The fracture is uneven to flat conchoidal. $H = 5.5 - 6$; $G = 2.4 - 2.5$.

Hauynite is $Na_2Ca(NaSO_4Al)Al_2Si_3O_{12}$. Potassium may be present. What was said above under noselite, of course applies here as to the chemical composition. Noselite is decomposed by hydrochloric acid and gelatinous silica separates out.

The luster is vitreous or greasy. The color is bright blue, sky blue, greenish blue, asparagus green, yellow, and colorless. The streak is slightly blue to colorless. The mineral is subtransparent to translucent. It is isotropic, but occasionally shows weak double refraction. The index of refraction is 1.4961.

For method of distinguishing hauynite from noselite, see under noselite.

Leucite.—At 500° leucite crystallizes in the isometric system. Under ordinary conditions of temperature it is pseudo-isometric. The usual form is the icositetrahedron. It is also found in disseminated grains and rarely as massive granular. The cleavage is very imperfect. Fracture is conchoidal, $H = 5.5 - 6$; $G = 2.45 - 2.50$. The twining is generally lamellar polysynthetic.

Leucite is a metasilicate of aluminium and potassium, $KAl(SiO_3)_2$. Occasionally small quantities of sodium are present. In addition to sodium, traces of lithium, rubidium, and caesium have been detected. It is infusible. Hydrochloric acid decomposes it without gelatinization. Leucite is not a very stable mineral.

Above 500° leucite is isotropic. Thin sections of small crystals are isotropic at ordinary temperatures. Crystals of larger size show weak double refraction of a faint bluish gray. The luster is vitreous. The color is white, ash-gray, and smoke-gray. The streak is uncolored. Translucent to opaque. The index of refraction is near 1.508.

Leucite resembles most closely sodalite and analcite; but its index of refraction is higher than the index of either of these minerals.

Spinel.—The term spinel is used both to designate a group of minerals to which some 20 varieties belong, among them magnetite, chromite, etc., and to designate a particular mineral of this group. The name here is used in this latter sense.

Spinel crystallizes in the isometric system. The usual form is the octahedron, occasionally modified by the dodecahedron. It is also

found as angular and subangular crystals and more rarely as cubes. The cleavage is rather imperfect. The fracture is conchoidal, H=8; G=3.5–4.1.

Spinel is a magnesium aluminate, $MgAl_2O_4$. Ferrous iron and manganese may partly replace the magnesium; and ferric iron and chromium may replace more or less the aluminum. It is infusible. Heating changes the red variety to brown, and on cooling it becomes green, then almost colorless, and finally resumes the true color. Concentrated sulphuric acid dissolves it with difficulty.

Spinel is transparent to nearly opaque. The luster is vitreous, splendent, and dull. The color is red, blue, green, yellow, brown, black, and sometimes almost white. The streak is white. The index of refraction high, varying from 1.7121 to 1.7261. In red light it is phosphorescent.

Spinel, including its subvarieties, ceylonite, chlorospinel, and picotite, closely resembles chromite from which it can be distinguished only by its hardness, specific gravity, and chemical composition. Spinel proper also resembles some of the garnets. The test for silicon or the difference in specific gravity serves to distinguish the two minerals.

GARNET GROUP.

The Garnet group contains several well-marked varieties. Only the following will be considered here: Grossularite, spessartite, almandite, and pyrope.

Grossularite.—Grossularite, in common with the other members of the garnet group, crystallizes in the isometric system. The dodecahedron and tetragonal trisoctahedron are the most common forms. It also occurs in grains, massive, granular, and compact forms. The fracture is uneven to subconchoidal. H=6.5–7.5; G=3.15–4.3.

Grossularite is a calcium aluminum silicate, $Ca_3Al_2(SiO_4)_3$. It fuses rather easily. After ignition it is decomposed by hydrochloric acid. Fusion with alkaline carbonates decomposes it. The luster is vitreous to resinous. The color is white, pale green, amber yellow, honey yellow, wine yellow, brownish yellow, cinnamon brown, pale rose red, and sometimes emerald green. It is isotropic, but usually exhibits weak double refraction. This double refraction varies in different parts of the same crystal. The index of refraction is high, varying from 1.7394 to 1.7617.

Spessartite.—Spessartite is a manganese-aluminum silicate, $Mn_3Al_2(SiO_4)_3$. Ferrous iron may replace the manganese partly, and ferric iron the aluminum. The color is a dark hyacinth red, sometimes tinged with violet, and brownish red. G=4.0–4.3. The index of refraction varies from 1.8050 to 1.8158. The difference in the index of refraction serves to distinguish this mineral from grossularite.

Almandite.—Almandite is an iron-aluminum silicate, $Fe_3Al_2(SiO_4)_3$. Ferric iron may replace the aluminum to some extent. Magnesium may also replace partly the ferrous iron. G = 3.9–4.2. The color is a fine deep red, brownish red, or black. The index of refraction varies from 1.8022 to 1.8159. Chemical means afford the best method of distinguishing this mineral; also some light may be thrown on its character by the color and by the fact that it fuses to a magnetic globule.

Pyrope.—Pyrope is a magnesium-aluminum silicate, $Mg_3Al_2(SiO_4)_3$. Calcium and iron may also be present. G = 3.7–3.75. The color varies from deep red to nearly black. The index of refraction varies from 1.7369 to 1.7545. When perfectly transparent it is prized as a gem.

Chromite.—See *Chromite* under *Opaque minerals.*

Perovskite.—Perovskite crystallizes in the isometric or pseudoisometric system. The crystal habit is generally cubic. The cleavage is cubic and rather perfect. The fracture is subconchoidal to uneven. H = 5.5; G = 4.017.

Perovskite is a calcium titanite, $CaTiO_3$. Iron or one of the cerium elements may partly replace the calcium. It is infusible. It is entirely decomposed by boiling sulphuric acid.

Optically, perovskite is transparent to opaque. The luster is adamantine to metallic adamantine. The color is pale yellow, honey yellow, orange yellow, reddish brown, grayish black, grayish white, violet gray, brownish to reddish, and rarely greenish. There is sometimes present a zonal arrangement of colors. Streak colorless or grayish. Microscopic crystals are isotropic; but larger crystals show anomalous double refraction, and are biaxial and usually positive. The reason for this is not definitely known. The index of refraction is high, 2.38.

Nearly opaque perovskite resembles hematite and ilmenite. Its insolubility in hydrochloric acid distinguishes it from these two minerals. When transparent, perovskite resembles chromite. From this it can be distinguished chemically.

ANISOTROPIC, UNIAXIAL MINERALS.

Tridymite.—Tridymite crystallizes in the hexagonal or pseudohexagonal system. The crystals are usually minute, thin, hexagonal plates. The fracture is conchoidal. H = 7; G = 2.28–2.33.

Tridymite is *silicon dioxide, silica,* SiO_2. It is soluble in boiling sodium carbonate.

Tridymite is colorless to white, transparent, and has a vitreous or pearly luster. The index of refraction is in the neighborhood of 1.476. The double refraction is weak, and the mineral is optically positive (+).

Chabazite.—Chabazite crystallizes in the rhombohedral system. The usual form is the simple rhombohedron. The angle is very near that of the cube, for which reason the two forms may be at first confused. It is sometimes amorphous. Penetration twins are very common. The fracture is uneven. H = 4–5; G = 2.08–2.16.

The chemical composition is variable. It is mostly (Ca, Na_2) $Al_2(SiO_3)_4 + 6H_2O$. Potassium is also present in small quantities, and chabazites have been found which contained barium and strontium. It fuses with intumescence. It is decomposed by hydrochloric acid, with the separation of gelatinous silica. The luster is vitreous. The color is white, flesh red, and colorless. The streak is uncolored. It is transparent to translucent. It is optically negative (−), but is positive (+) when containing a higher percentage of water. The interference figure is usually confused. The mean index of refraction is 1.5. The crystals are divided into sectors having different optical orientations.

Cancrinite.—Cancrinite crystallizes in the hexagonal system. It is usually massive. H = 5–6; G = 2.42–2.5. The cleavage is perfect parallel to m(1010).

Cancrinite is $H_6Na_6Ca(NaCO_3)_2Al_8(SiO_4)_9$. In the closed tube it gives water. Its very easy fusibility distinguishes it from nephelite. It is decomposed by hydrochloric acid with the evolution of carbon dioxide. On heating gelatinous silica forms.

The color is white, gray, yellow, green, blue, reddish, and colorless. The streak is uncolored. The luster is subvitreous to pearly or greasy. The mineral is transparent to translucent. It is optically negative (−). The index of refraction varies from 1.4955 to 1.5244. The double refraction is strong.

Cancrinite resembles orthoclase. Its strong double refraction serves as a method for distinguishing the two.

Apophyllite.—Apophyllite crystallizes in the tetragonal system. Usually in square prisms or acute pyramidal forms; also granular, lamellar, and rarely concentrically radiated. Cleavage parallel to (001) perfect; cleavage parallel to (110) less perfect. The fracture is uneven, H = 4.5–5; G = 2.3–2.4.

Apophyllite is $H_7KCa_4(SiO_3)_8 + 4\frac{1}{2}H_2O$. Fluorine replaces part of the oxygen. Yields water, whitens, and exfoliates in the closed tube. Hydrochloric acid decomposes it with the separation of gelatinous silica.

The luster is pearly and vitreous. The color is white, grayish, flesh red, and greenish, yellowish and rose tints, and colorless. Optically positive (+), sometimes negative (−). The index of refraction varies from 1.5309 to 1.5369. The double refraction is very low. Apophyllite resembles the zeolites, but has a higher refraction than most of them. It differs from chabazite in having basal cleavage.

Nephelite.—Nephelite crystallizes in the hexagonal system. It is usually in thick 6-sided or 12-sided prisms; also massive and in embedded grains. The fracture is subconchoidal. H = 5 – 5.5; G = 2.55 – 2.65.

Nephelite is $K_2Na_6Al_8Si_9O_{34}$. Iron, magnesium, and calcium may also be present. It fuses quietly to a colorless glass. It is attacked by hydrochloric acid and gives gelatinous silica.

The luster is vitreous to greasy and opalescent. The color is white, yellowish, dark green, greenish or bluish gray, brownish red and brick red, and colorless. It is transparent to opaque. It is optically negative (–). The double refraction is low, and very thin sections do not yield an interference figure. The index of refraction varies from 1.5376 to 1.5469.

Nephelite in thin sections resembles quartz, feldspar, and apatite. Its index of refraction is lower than that of apatite and it lacks the rough surface and relief of the latter. It is somewhat lower than quartz in double refraction, is negative, does not yield an interference figure in very thin sections, exhibits cleavage, and shows alteration not found in quartz. Nephelite differs from unstriated feldspar in that the refraction of nephelite is noticeably higher. Unstriated andesine has a slightly higher double refraction and exhibits a biaxial interference figure.

Quartz.—Quartz crystallizes in the rhombohedral system. The usual form found in soils is as irregular grains. Occasionally six-sided hexagonal forms are found. Fracture conchoidal to subconchoidal, and uneven to splintery, in some massive forms. H = 7; G = 2.653.

Quartz is silica, SiO_2. It may be rendered impure by admixtures of iron oxide, calcium carbonate, clay, and other minerals contained in the quartz as inclusions. It is infusible. In soda it dissolves with effervescence. It is soluble only in hydrofluoric acid.

The luster is vitreous, occasionally greasy, and splendent to almost dull. The pure varieties are colorless, but, owing to impurities, it may be yellow, red, brown, green, blue, black. With the pure varieties the streak is white. In the impure varieties the streak is often of the same color as the mineral, only paler. It is transparent to opaque. It is optically positive (+). The double refraction is weak. The polarization is circular; hence the axial figure has a colored center. The index of refraction varies from 1.54418 to 1.55328. It has various inclusions of other minerals, liquids, and gases.

Quartz is by far the most abundant of soil particles. Once recognized under the microscope it can not well be confused with any other mineral.

Wernerite.—Wernerite crystallizes in the tetragonal system. It occurs as coarse crystals with rough uneven faces, and massive granular, columnar, and faintly fibrous. The fracture is subconchoidal. H = 5–6; G = 2.66–2.73. The cleavage is rather distinct, but is interrupted.

Wernerite is intermediate between meionite and marialite. It corresponds to a molecular combination of these in a ratio of from 3:1 to 1:2. The composition of meionite is $Ca_4Al_6Si_6O_{25}$. This is represented by the symbol Me. The composition of marialite is $Na_4Al_3Si_9O_{24}Cl$. This is represented by the symbol Ma. Therefore, wernerite may be represented as Me_3Ma_1 to Me_1Ma_2. It easily fuses with intumescence to a white blebby glass. Hydrochloric acid decomposes it imperfectly.

The luster is vitreous and pearly, inclining to resinous. The color is white, gray, bluish, greenish, and reddish. The streak is uncolored. The mineral is transparent to faintly subtranslucent. Optically, it is negative (−). The double refraction is weak. The index of refraction varies from 1.545 to 1.566. Wernerite may be distinguished from the feldspars usually by the higher double refraction and by uniaxial characters. It differs from quartz in being optically negative.

Beryl.—Beryl crystallizes in the hexagonal system. The crystals are usually long prismatic, occasionally massive, columnar, granular, or compact. The fracture is conchoidal to uneven. H = 7.5–8; G = 2.63–2.80.

Beryl is $Be_3Al_2Si_6O_{18}$. Sodium, lithium, and caesium sometimes partly replace the beryllium. Chemically combined water may also be present. The fusibility is rather high, 5.5. It is unacted upon by acids.

The luster is vitreous and resinous. The color is emerald green, pale green, light blue, yellow, white, and pale rose red. The streak is white. Beryl is transparent to subtransparent. It is optically negative (−). It is often abnormally biaxial. The double refraction is feeble. The index of refraction varies from 1.5720 to 1.58935.

Tourmaline.—Tourmaline crystallizes in the rhombohedral system. The crystals are usually prismatic, and often slender and acicular. They are often rounded to barrel-shaped. It is sometimes massive, compact, or columnar. The fracture is subconchoidal to uneven. H = 7–7.5; G = 2.98–3.20.

Tourmaline is a complex silicate of boron and aluminum, with magnesium, iron, or the alkali metals present. The exact formula is uncertain. The different kinds are classed as alkali tourmalines, iron tourmalines, magnesium tourmalines, and chromium tourmalines. The formulas are something like the following:

$$12\ SiO_2 3B_2O_3 8Al_2O_3 2Na_2O 4H_2O$$
$$12\ SiO_2 3B_2O_3 5Al_2O_3 12MgO 3H_2O$$

The fusibility varies with the composition. It is not decomposed by acids. After fusion, sulphuric acid perfectly decomposes it, and it gelatinizes with hydrochloric acid.

The luster is vitreous to resinous. The color is black, brownish black, bluish black, blue, green, red, and rarely white, and colorless. The color may vary in the same specimen, the internal part being red and the external green, or the ends may be differently colored. The streak is uncolored. Tourmaline is transparent to opaque, and strongly pleochroic. It is optically negative (−). Sometimes, from molecular strain, it is anomalously biaxial. The double refraction is moderate. The index of refraction, which varies with the composition, ranges from 1.6195 to 1.6530.

Tourmaline resembles apatite when colorless, but it has a much stronger double refraction.

Apatite.—Apatite crystallizes in the hexagonal system. The crystals vary from long to short prismatic. Apatite is also massive, granular, or compact. The cleavage is rather imperfect. The fracture is conchoidal to uneven, H = 5. The hardness of the massive varieties is sometimes as low as 4:5. G = 3.17–3.23. The name phosphorite is applied to apatite in fibrous concretionary forms. Osteolite is the earthy form.

Apatite is a tricalcium phosphate containing either chlorine or flourine or both. The chlorine and fluorine are present generally in the form of calcium chloride or calcium fluoride. The general formula is $(Ca(F,Cl)Ca_4(PO_4)_3$. This may be written as either $(3CaO.P_2O_5)_3+CaF_2$ or $(3CaO.P_2O_5)_3+CaCl_2$. Some apatites contain the hydroxyl (OH), others a considerable amount of manganese. Traces of didymium, cerium, and lanthanum have also been detected in certain cases. It fuses with difficulty. It is soluble in both hydrochloric and nitric acids. Some varieties phosphoresce on heating. Dissolved in hydrochloric acid and ammonium molybdate added, there is given a copious precipitate of ammonium phosphomolybdate, which is of a peculiar yellow color. This test can be utilized under the microscope.

The luster is vitreous, inclining to subresinous. The streak is white. The color is sea-green, bluish green, violet blue, white, yellow, gray, red, flesh-red, and brown. Under the microscope the mineral is usually colorless. It is transparent to opaque. Some of the colored varieties are pleochroic. It is optically negative (−). The double refraction is weak. The index of refraction varies from 1.6287 to 1.6449. Occasionally it is anomalously biaxial.

Apatite usually presents characteristic appearances. The ordinary optical test is usually sufficient for its identification.

Calcite.—Calcite crystallizes in the rhombohedral system. It usually occurs well crystallized, the crystals sometimes having great

complexity of form. It also occurs in fibrous, granular, compact, earthy, stalactitic, and nodular forms. The cleavage is highly perfect and characteristic. The fracture is not easy to obtain owing to the ease of cleavage; but when obtained is conchoidal, H=3; G=2.713.

Calcite is calcium carbonate, $CaCO_3$. Magnesium, iron, manganese, zinc, and lead may be present, replacing the calcium. Numerous other mechanically admixed impurities may be present. It is infusible; but on heating is converted into lime, CaO, which reacts alkaline to litmus. Moistened with hydrochloric acid, it gives the ordinary flame coloration for calcium. It effervesces briskly with cold dilute acids.

The luster is vitreous, subvitreous, or earthy. It is usually white to colorless, but may be gray, red, green, blue, violet, yellow, brown, or black. The streak is white or grayish. It is transparent to opaque. Optically, it is negative (−). The double refraction is strong. The index of refraction varies between 1.48625 and 1.65849.

Calcite is very quickly acted upon by cold dilute acids, whereas dolomite is only very slowly acted upon. This serves as a method for distinguishing the two.

Dolomite.—Dolomite crystallizes in the rhombohedral system. The crystals often have rounded faces and edges. It also occurs in amorphous or granular forms. The cleavage is perfect. The fracture is subconchoidal. H=3.5–4; G=2.8–2.9.

Dolomite is a calcium-magnesium carbonate, $(Ca,Mg)CO_3$. Carbonates of iron, manganese, and rarely of cobalt and zinc, may enter into the compound. It acts very much as calcite does, with the exception of effervescing very much slower in cold dilute acids.

The luster is vitreous, sometimes inclining to pearly. The color is white, reddish or greenish white, rose-red, green, brown, gray, and black. It is transparent to translucent. Optically it is negative (−). The index of refraction runs from 1.50256 to 1.68174.

For distinction from calcite, see under "*Calcite*" above.

Corundum.—Corundum crystallizes in the rhombohedral system. In soils it usually occurs as grains. The fracture is uneven to conchoidal. H=9; G=3.95–4.10.

Corundum is alumina, Al_2O_3. After long heating with cobalt nitrate solution, the finely pulverized mineral gives a blue color. It is unacted upon by acids.

The luster is adamantine to vitreous. The color is red, blue, yellow, brown, gray, and nearly white. The streak is uncolored. Transparent to translucent. The deeply colored varieties are pleochroic. It is optically negative (−). Large twinned crystals are often abnormally biaxial. The double refraction often varies within the same crystal. The index of refraction is high, running

from 1.7592 to 1.7690. The double refraction is slightly less than that of quartz.

Corundum resembles quartz, nephelite, and apatite. Its higher index of refraction distinguishes it from these minerals.

Zircon.—Zircon crystallizes in the tetragonal system. It is commonly in square prisms and also in grains. The cleavage is imperfect. The fracture is conchoidal. H=7.5; G=4.68–4.70. It is sometimes geniculated.

Zircon is zirconium silicate, $ZrSiO_4$. Ferric iron is usually present, and occasionally calcium and magnesium. It is infusible. Acids do not act upon it, except in the case of sulphuric acid with very fine powders. Fusion with alkaline carbonates and bisulphates decomposes it.

The luster is adamantine. The color is pale yellowish, grayish, yellowish green, brownish yellow, reddish brown, and colorless. The streak is uncolored. It is transparent to subtranslucent and opaque. It is optically positive (+). Some large crystals are abnormally biaxial. Alteration may cause it to become isotropic and amorphous. The double refraction is high. The index of refraction varies from 1.9239 to 2.015.

In microscopic crystals it is well characterized by its brilliant interference colors and crystal form.

Siderite.—Siderite crystallizes in the rhombohedral system. The crystals are usually rhombohedral with curved faces; and often massive or granular, fibrous, compact, and earthy. The cleavage is perfect. The fracture is subconchoidal to uneven. H=3.5–4.0; G=3.83–3.88.

Siderite is an iron proto-carbonate, $FeCO_3$. Manganese, magnesium, and calcium may also be present. It fuses at 4.5. Cold dilute acid acts upon it very slowly, but in hot acid it effervesces briskly.

The luster is vitreous, inclining to pearly. The color is ash-gray, yellowish gray, greenish gray, brown, brownish red, rarely green, and white. The streak is white. It is translucent to subtranslucent. The double refraction is strong. It is optically negative (−). The index of refraction varies from 1.6219 to 1.9341.

Generally speaking, the index of refraction of siderite is higher than that of any other minerals with which it may be confounded. Chemical means, however, furnish the best methods of identification.

Anatase (*Octahedrite*).—Anatase crystallizes in the tetragonal system. It is usually octahedral in habit, either acute or obtuse. It also occurs in tabular form and rarely as prismatic crystals. The cleavage is perfect. The fracture is subconchoidal. H=5.5–6; G=3.82–3.95.

Anatase is titanium dioxide, TiO_2. It is infusible. It is insoluble in acids, but is made soluble by fusion with an alkali or alkaline carbonate.

The luster is adamantine or metallic-adamantine. The color is brown, indigo blue, and black. In transmitted light it is greenish yellow. It is somewhat pleochroic. The streak is uncolored. It is transparent to nearly opaque. Optically, it is negative (−). The double refraction and dispersion are rather strong. The index of refraction varies from 2.4523 to 2.6066. Darker colored portions are sometimes biaxial.

This mineral is of rare occurrence.

Rutile.—Rutile crystallizes in the tetragonal system. The forms are often geniculated. The crystals are usually prismatic or acicular. Sometimes it is compact or massive. The cleavage parallel to (110) and (100) is distinct. The fracture is subconchoidal to uneven. H = 6–6.5; G = 4.18–4.25.

Rutile is titanium dioxide, TiO_2. Iron is usually present. Chromium and tin are sometimes present. It is infusible. It is insoluble in acids, but it is made soluble by fusion with an alkali or alkaline carbonate.

The luster is metallic adamantine. The color is reddish brown, passing into red, yellowish, bluish, violet, black, and rarely grass-green. In transmitted light it is light yellow, fox red, brownish red, or violet. The streak is pale brown. It is transparent to opaque. It is optically positive (+). The double refraction is strong. The index of refraction runs from 2.5671 to 2.9817. In some cases it is abnormally biaxial. It is variably pleochroic.

Rutile resembles zircon. Its higher refraction and double refraction, however, distinguish it. Its optical character, positive or negative, distinguishes it from anatase.

Hematite.—See *Hematite* under *Opaque Minerals.*

ANISOTROPIC, BIAXIAL MINERALS.

Natrolite.—Natrolite crystallizes in the orthorhombic system. The crystals are prismatic and are usually very slender to acicular. It is also fibrous, radiating, massive, granular, or compact. The cleavage parallel to (110) is perfect. The fracture is uneven. H = 5–5.5; G = 2.20–2.25.

Natrolite is $Na_2Al_2Si_3O_{10}+2H_2O$. It fuses quietly at a comparatively low temperature. It gelatinizes with acids.

The luster is vitreous, inclining to pearly. The color is white grayish, yellowish, reddish to red, and colorless. In thin sections it is colorless. It is transparent to translucent. Optically it is positive (+). The index of refraction varies from 1.47287 to 1.49296. It has parallel extinctions usually; but some specimens have been found to show extinction inclined from 5° to 7° to the prismatic edge. Some specimens are apparently monoclinic.

The usual parallel extinction distinguishes natrolite from scolecite and laumontite. It also has higher double refraction than scolecite.

Phillipsite.—Phillipsite crystallizes in the monoclinic system. The crystals are uniformly penetration twins, often simulating orthorhombic or tetragonal forms. They are separate or clustered. The cleavage parallel to (001) and (010) is rather distinct. The fracture is uneven. H=4–4.5; G=2.2.

Phillipsite is $(K_2,Ca)Al_2(SiO_3)_4+4\frac{1}{2}H_2O$. Sodium and barium are sometimes present. At 3 it crumbles and fuses to a white enamel. It gelatinizes with hydrochloric acid.

The luster is vitreous. The color is white, occasionally reddish. In thin sections it is colorless. The streak is uncolored. It is translucent to opaque. Optically it is positive (+). The double refraction is very low. The index of refraction for β varies from 1.51 to 1.57. The angle of extinction is inclined up to 18°. The dispersion is slight.

Chabazite.—See *Chabazite* under *Anisotropic, Uniaxial Minerals.*

Heulandite.—Heulandite crystallizes in the monoclinic system. The crystals are sometimes flattened parallel to (010). It also occurs in globular and granular forms. The cleavage parallel to (010) is perfect. The fracture is subconchoidal to uneven. H=3.5–4; G=2.18–2.22.

Heulandite is $H_4CaAl_2\ (SiO_3)_6+3H_2O$. Strontium is usually present. On heating it exfoliates, swells up, curves into fanlike or vermicular forms, and fuses. Hydrochloric acid decomposes it without gelatinization.

The luster is pearly and vitreous. The color is various shades of white, red, gray, and brown. It is colorless in thin sections. The streak is white. It is transparent to translucent. Optically, it is positive (+). The double refraction is weak. The index of refraction runs from 1.498 to 1.505.

Scolecite.—Scolecite crystallizes in the monoclinic system. The crystals are slender prisms. It also occurs massive, fibrous, and radiated, and in nodules. The cleavage parallel to (110) is nearly perfect. H=5–5.5; G=2.16–2.4.

Scolecite is $CaAl_2Si_3O_{10}+3H_2O$. Sodium may be present in some instances. It fuses rather easily. With acids it gelatinizes.

The luster is vitreous, or silky when fibrous. The color is white, or, in thin section, colorless. It is transparent to subtranslucent. It is optically negative (−). The fibers have inclined extinction of about 15°. The double refraction is low. The index of refraction varies from about 1.4952 to 1.502.

Laumontite.—Laumontite crystallizes in the monoclinic system. It occurs in prismatic, columnar, radiating, and divergent forms. The cleavage parallel to (010) and (110) is very perfect. The fracture is uneven. H=3.5–4; G=2.25–2.36.

Laumontite is $H_4CaAl_2Si_4O_{14}+2H_2O$. Iron, sodium, potassium, and magnesium may be present. On heating, it swells up and fuses to a white enamel. It gelatinizes with hydrochloric acid.

The luster is vitreous, inclining to pearly on cleavage faces. The color is white, yellow, gray, and sometimes red. The streak is uncolored. Thin sections are colorless. It is transparent to translucent. Exposure causes it to become opaque and usually pulverulent. Optically, it is negative (−). The double refraction is stronger than that of quartz. The index of refraction varies from 1.513 to 1.525. The maximum extinction angle is 30°.

Gypsum.—Gypsum crystallizes in the monoclinic system. The common forms are flattened, prismatic, or acicular. It also occurs in massive, granular massive, and impalpable forms. The crystals are often warped. The cleavage parallel to (010) is eminent, yielding folia. H = 1.5–2; G = 2.314–2.328.

Gypsum is a hydrous calcium sulphate, $CaSO_4+2H_2O$. In the closed tube it gives water and becomes opaque. It fuses rather readily. It is soluble in hydrochloric acid, and in from 400 to 500 parts of water.

The luster on the face (010) is pearly and shining. On other faces the luster is subvitreous. It is sometimes glistening or dull earthy. The color is white, gray, flesh red, honey yellow, ocher yellow, blue, and in impure varieties may be black, brown, red, or reddish brown. In thin sections it is colorless. The streak is white. It is transparent to opaque. Optically, it is a positive (+). The double refraction is low. The index of refraction varies from 1.5204 to 1.5305. The extinction is inclined.

Orthoclase.—H = 6; $KAlSi_3O_8$. It is fusible; and is not acted upon by acids. Soda may be present.

The luster is vitreous; on cleavage faces it is pearly. The color is white, pale yellow, flesh-red, gray, rarely green, and colorless. (See under Feldspars.)

Orthoclase is a very common soil-forming mineral, and its appearance is usually characteristic. It may be confounded with the other feldspars, but may be distinguished from them by its angle of extinction. Its lower index of refraction and biaxial character distinguishes it from quartz.

Microcline.—The fracture is uneven. H = 6–6.5. Sodium is usually present. Iron, magnesium, and calcium may sometimes be present.

The luster is vitreous or pearly. The color is white, pale cream-yellow, red, and green. It is transparent to translucent. (See under Feldspars.)

Albite.—The crystals are often tabular or elongated. It is also massive, either lamellar or granular. The fracture is uneven to conchoidal. H = 6–6.5.

Small amounts of calcium are usually present. Potassium, iron, and magnesium may also be present. It fuses to a colorless or white glass, giving an intense yellow to the flame. It is unacted upon by acids.

The luster is vitreous; on a cleavage surface often pearly. The color is white, bluish, gray, reddish, greenish, and green. The streak is uncolored. It is transparent to subtranslucent. (See under Feldspars.)

Chrysotile.—Chrysotile crystallizes in the monoclinic or orthorhombic (?) system. Distinct crystals are always pseudomorphs after other crystals, usually after the mineral from which the chrysotile has been derived. The usual form is fibrous. They are usually prismatic and are often flexible and silklike. The cleavage is prismatic, the angle being 50°. It has a smooth, sometimes greasy feel. H = 2.5–4, sometimes as high as 5.5. G = 2.50–2.65.

Chrysotile is a hydrous magnesium silicate, $H_4Mg_3Si_2O_9$. Iron protoxide often replaces part of the magnesium. Nickel is also sometimes present in small amounts. Aluminum, calcium, ferric iron, chromium, alkalies, and manganese may be present. It yields water in the closed tube. It is fusible only on the edges, and there with difficulty. Hydrochloric and sulphuric acids decompose it. The silica is left in fine fibers.

The luster is subresinous to greasy, pearly, earthy, resinlike, or waxlike. The color is leek green, blackish green, oil green, siskin green, brownish red, brownish yellow, nearly white. None of the colors are bright. Exposure often causes it to become yellowish gray. The streak is white and slightly shining. It is translucent to opaque. The pleochroism is feeble. It is biaxial and optically positive (+). The index of refraction is about 1.54. The double refraction is a little higher than that of quartz. The extinction of the fibers is parallel.

Kaolin.—Kaolin crystallizes in the monoclinic system. The usual form is thin rhombic, or hexagonal plates parallel to (001). It also occurs as irregularly shaped scales. The mineral occurs chiefly in claylike masses, compact, friable, or mealy. The cleavage parallel to the base (001) is perfect. H = 2–2.5; G = 2.6–2.63.

Kaolin is a hydrated aluminum silicate, $H_4Al_2Si_2O_9$. Ferric iron, fluorine, calcium, magnesium, and carbon dioxide may be present. On heating, it yields water. It is infusible. It is insoluble in hydrochloric acid, but is slowly soluble in hot sulphuric acid.

The luster of the plates is pearly. That of the mass is pearly to dull earthy. The color is white, grayish white, yellowish, brownish, bluish, or reddish. The scales are transparent to translucent. The mass is usually unctuous and plastic. It is biaxial, and optically negative (−). The double refraction is low. The index of refraction is about 1.54.

Kaolin forms the larger portion of the clayey matter of soils. Often the individual grains are far too small for accurate identification.

Cordierite (Iolite).—Cordierite crystallizes in the orthorhombic system. It is commonly in penetration twins with pseudohexagonal forms. It has a short prismatic crystal habit, and also occurs as grains, and in massive and compact forms. The cleavage parallel to (010) is distinct. The fracture is subconchoidal. H = 7–7.5; G = 2.60–2.66.

Cordierite is $H_2(Mg,Fe)_4Al_8Si_{10}O_{37}$. Ferrous iron may replace part of the magnesium. Calcium, manganese, and occasionally lithium, may be present. On heating it loses its transparency and fuses. Acids only partly decompose it. Fusion with alkaline carbonates decomposes it.

The luster is vitreous. The color is various shades of blue, grayish, and yellowish. Thin sections are colorless. It is transparent to translucent. Thick sections are distinctly pleochroic; thin sections less so or not at all. It is optically negative (−). The double refraction is variable. The index of refraction varies from 1.532 to 1.5992, usually it approximates 1.55.

Cordierite resembles quartz, but is distinguished from the latter by its biaxial character.

Chalcedony.—The crystalline system of chalcedony has not been established. It occurs in aggregates of radiating or parallel fibers. The cross section of these fibers is irregular. H = 7; G = 2.59–2.64.

Chalcedony is silica, SiO_2, like quartz.

The color is white, grayish, pale brown, dark brown, black, tendon color, sometimes delicate blue. In thin sections it is colorless. The double refraction is only slightly lower than that of quartz. The index of refraction is 1.537. The fibers have parallel extinction. Chalcedony is optically negative and is thus distinguished from quartz. The luster is waxlike.

Oligoclase.—The usual form is massive, cleavable to compact. Crystals are uncommon. The fracture is conchoidal to uneven. H = 6–7. It fuses to a clear or enamellike glass. It is not materially acted upon by acids.

The luster is vitreous to pearly or waxy. The color is usually whitish, with a tinge of grayish green, grayish white, reddish white, greenish, reddish, and sometimes aventurine. It is transparent to subtranslucent. (See under Feldspars.)

Andesine.—It occurs usually as massive cleavable or granular. Thin splinters fuse before the blowpipe. It is imperfectly soluble in acids.

The luster is subvitreous to pearly. The color is white, gray, greenish, yellowish, and flesh red. (See under Feldspars.)

Labradorite.—It occurs in tabular, equant, and prismatic forms. Massive, cleavable, granular, and cryptocrystalline forms also occur. The fracture, in directions other than cleavage directions, is uneven. In certain cases the fracture is conchoidal. H = 5 – 6. It fuses to a colorless glass. Hydrochloric acid decomposes it with difficulty, generally leaving a residue of the undecomposed mineral.

The luster on (001) is pearly to vitreous. On other faces it is vitreous to subresinous. The mineral is gray, brown, greenish, white, and colorless. Cleavable varieties usually display a beautiful play of colors. The streak is uncolored. It is translucent to opaque. Optically positive. (See under Feldspars.)

Antigorite.—The structure of antigorite is thin lamellar. It can easily be separated into translucent or subtransparent folia. The cleavage is pinacoidal, and is sometimes distinct. The fracture in the massive varieties is splintery to subconchoidal, H = 2.5. G = 2.622.

Antigorite is identical with chrysotile, a hydrous magnesium silicate, $H_4Mg_3Si_2O_9$. The same impurities occur in this mineral as in chrysotile. Hydrochloric and sulphuric acids decompose it.

By transmitted light the color is leek green; by reflected light it is brownish green. The streak is white. It is translucent to opaque. The pleochroism is feeble. It is optically negative (–). The double refraction is slightly higher than that of quartz. It is biaxial; and the index of refraction runs from 1.56 to 1.571.

The negative (–) optical character distinguishes this mineral from chrysotile.

Anhydrite.—Anhydrite crystallizes in the orthorhombic system. Crystals are uncommon. The usual forms are massive, cleavable, fibrous, lamellar, granular, and impalpable. The cleavage parallel to (001) is very perfect. Cleavage in three directions gives the cleavage fragments a cubical appearance. The fracture is uneven to splintery. H = 3–3.5; G = 2.899–2.985.

Anhydrite is anhydrous calcium sulphate, $CaSO_4$. It fuses and imparts to the flame a reddish-yellow color. The bead obtained from the fusion is enamellike and reacts alkaline. It is soluble in hydrochloric acid. Through the absorption of water it alters to gypsum.

The luster is pearly on (001); greasy on (100); and vitreous on (010). The color is white, grayish, bluish, reddish, and brick-red. Thin sections are colorless. Optically, it is positive (+). The double refraction is high. The index of refraction varies from 1.5693 to 1.6138.

Anhydrite is not likely to be confused with any other mineral. Its optical properties and cleavage are characteristic.

Talc.—The crystallization of talc is either orthorhombic or monoclinic (?). The usual forms are foliated massive, granular-massive, fibrous, compact, cryptocrystalline, and sometimes in globular and

stellated groups. The cleavage parallel to (001) is perfect. The laminæ are flexible, but are not elastic. H=1; G=2.7–2.8. The feel is greasy.

Talc is an acid metasilicate of magnesium, $H_2Mg_3(SiO_3)_4$. Nickel, iron, calcium, aluminum, manganese, sodium or strontium may be present. Most varieties yield water in the closed tube when intensely ignited. On heating, it whitens, exfoliates, and fuses with difficulty on thin edges. It gives the magnesium reaction (a pale flesh-red color) with cobalt nitrate solution. Acids do not decompose it.

The luster is pearly on cleavage surfaces. The color is apple green, white, silvery white, greenish gray, dark green, and brownish to reddish when impure. Thin sections are colorless. It is biaxial. Optically, it is negative (−). The double refraction is high. The index of refraction runs from 1.539 to 1.589.

Talc resembles sericite, from which it must be distinguished chemically.

Vivianite.—Vivianite crystallizes in the monoclinic system. The forms are prismatic, reniform, globular, fibrous, and earthy. The cleavage parallel to (010) is perfect. The fracture is fibrous. H=1.5–2; G=2.58–2.68.

Vivianite is a hydrous ferrous-phosphate, $Fe_3P_2O_8+8H_2O$. In the closed tube it yields neutral water, whitens, and then exfoliates. It fuses rather easily to a magnetic globule, coloring the flame bluish green. It is soluble in hydrochloric acid.

The luster on (010) is pearly or metallic pearly; on the other faces it is vitreous. When unaltered it is colorless. Alteration causes it to assume a blue to green color. The streak is colorless to bluish white. It is transparent to translucent. Exposure causes it to become opaque. The pleochroism is strong. Optically it is positive (+). The index of refraction runs from 1.577 to 1.627.

Anorthite.—The crystals are usually prismatic. It also occurs massive, cleavable, granular, and coarse lamellar. The fracture is conchoidal to uneven. H=6–6.5.

It fuses to a colorless glass. Some anorthite is decomposed by hydrochloric acid, with the separation of gelatinous silica.

The color is white, grayish, and reddish. The streak is uncolored. It is transparent to translucent. See under Feldspars.

Pyrophyllite.—Pyrophyllite has not been observed in distinct crystals. The forms are foliated, radiated, lamellar, somewhat fibrous, granular, compact, and cryptocrystalline. The cleavage parallel to the base is eminent. The feel is greasy. H=1–2· G=2.8–2.9.

Pyrophyllite is a hydrous silicate of aluminum, $H_2Al_2Si_4O_{12}$. Iron, magnesium, or calcium may be present. At a high temperature it

yields water. On heating, it whitens and fuses on the edges with difficulty. The radiated varieties exfoliate in fanlike forms. The alumina test is obtained with cobalt nitrate solution. Sulphuric acid partially decomposes it. Fusion with alkaline carbonates completely decomposes it.

The luster of the folia is pearly, that of the massive kinds is dull and glistening. The color is white, apple green, grayish green, brownish green, yellowish, ocher yellow, and grayish white. It is subtransparent to opaque. Optically it is negative (−). The index of refraction is about 1.59.

Chlorite group.—Penninite, clinochlore, and prochlorite are the chief members of this group.

The chlorites crystallize in the monoclinic, sometimes pseudotrigonal, system. Clinochlore is often in tabular crystals flattened parallel to (001). The outline is hexagonal. Trigonal and rhombohedral crystals occur. The habit of penninite is rhombohedral (pseudorhombohedral); but the axes may be referred to the same monoclinic axes as clinochlore. The crystals are thick tabular and show trigonal outlines. Sometimes they are apparently rhombohedrons. Prochlorite does not assume the well-marked forms of the other two varieties. It occurs in 6-sided tables or prisms. Microscopic crystals of all these varieties appear as minute scales or fibers or as ill-defined particles. The twinning plane is perpendicular to (001). The cleavage parallel to (001) is perfect. The hardness varies in the different varieties from 1 to 2.25. G = 2.6 − 2.96.

The chemical composition of the group varies considerably. Clinochlore and penninite may be represented as $H_8(Mg, Fe)_5AlSi_3O_{18}$; prochlorite as $H_{40}(Fe, Mg)_{23}Al_{14}Si_{13}O_{90}$. Ferric iron, chromium, and manganese may be present, as well as small quantities of sodium, potassium, calcium, and nickel. In the closed tube the chlorites yield water. They fuse with difficulty. Sulphuric acid completely decomposes them.

The color is various shades of green, rarely brown, nearly colorless, and occasionally violet, rose red, and pink. The colored chlorites are noticeably pleochroic. In clinochlore the refraction index runs from 1.585 to 1.596; that of penninite from 1.575 to 1.5832. Clinochlore and prochlorite are generally biaxial and are optically positive (+). Penninite is uniaxial and sometimes optically positive (+) and sometimes optically negative (−).

Biotite.—Biotite crystallizes in the monoclinic system. It usually occurs as thin flakes or scales. The cleavage parallel to the base is highly perfect. H = 2.5 − 3; G = 2.7 − 3.1.

The chemical composition varies somewhat. In general it may be represented by the formula $(H, K)_2(Mg, Fe)_2(Al, Fe)_2(SiO_4)_3$. In the closed tube it gives a little water. On heating, it whitens and

fuses on thin edges. Sulphuric acid completely decomposes it, leaving the silica in thin scales.

Biotite is biaxial, but in some cases the angle is so small as to make it appear like a uniaxial crystal. It is optically negative (−). The index of refraction varies from 1.504 to 1.638, generally nearer the larger figure. The double refraction is strong. The color is usually green, brown, black, pale yellow, and rarely white. The luster is vitreous to pearly to submetallic.

The micas, of which biotite is a variety, can be distinguished from all other minerals by their pronounced cleavage. In general it may be said that the darker colored micas which exhibit nearly uniaxial interference figures are biotite.

Paragonite.—Paragonite occurs massive, in fine scales, and compact. The cleavage parallel to the base is eminent. H = 2.5–3; G = 2.78–2.90.

Paragonite is a sodium mica. The composition corresponds to that of muscovite. The formula is $H_2NaAl_3(SiO_4)_3$. It will be noticed that here sodium takes the place of the potassium in the muscovite formula. A little potassium is often present in paragonite. Before the blowpipe it fuses with difficulty.

The color is yellowish, grayish, greenish, light apple green, and colorless. The luster is strongly pearly. It is translucent; thin scales are transparent. It is optically negative (−). The index of refraction is near 1.60.

Chemical tests serve to distinguish it from muscovite and talc. Its lighter color and biaxial character distinguish it from biotite.

Pectolite.—Pectolite crystallizes in the monoclinic system. It is common in close aggregations of acicular crystals, and also fibrous, massive, and radiated to stellate. The cleavage parallel to (100) and (001) is perfect. The fracture is uneven. H = 5; G = 2.68–2.78.

Pectolite is an acid metasilicate of sodium and calcium, $HNaCa_2(SiO_3)_3$. In the closed tube it yields water. It fuses rather easily to a white enamel. Hydrochloric acid decomposes it, with the separation of gelatinous silica.

The luster is silky or subvitreous in the surface of fracture. The color is whitish or grayish. It is subtranslucent to opaque. Thin sections are colorless. Optically, pectolite is positive (+). The fibers show parallel extinction. The index of refraction is about 1.61.

Phlogopite.—Phlogopite crystallizes in the monoclinic system. The chief form in which it occurs is as thin flakes. The cleavage parallel to the base is highly eminent. H = 2.5–3; G = 2.78–2.85.

Phlogopite is a magnesium mica, very close to biotite, but contains a relatively small percentage of iron. The formula is written as $HK(MgF)_3Mg_3Al(SiO_4)_2$. It gives a little water in the closed tube.

On heating it whitens and fuses on thin edges. Sulphuric acid completely decomposes it, leaving the silica in thin scales.

The luster is pearly and submetallic on cleavage surfaces. The color is yellowish brown to brownish red, pale brownish yellow, green, white, and colorless. Thin folia are transparent to translucent. In colored varieties the pleochroism is distinct. Optically, it is negative (−). The index of refraction varies from 1.562 to 1.606.

Muscovite.—Muscovite crystallizes in the monoclinic system. It usually occurs as thin flakes. The cleavage is eminent parallel to the base. H = 2–2.5; G = 2.76–3.

This mica is mostly an orthosilicate of aluminum and potassium, $H_2KAl_3Si_3O_{12}$. It gives water in the closed tube. Before the blowpipe it whitens and fuses on thin edges. Acids do not decompose it. Fusion with alkaline carbonates decomposes it.

The luster is vitreous, pearly, or silky. The color is gray, brown, hair brown, pale green, violet, yellow, dark olive green, rarely rose red, and colorless. The streak is uncolored. It is transparent to translucent. Usually the pleochroism is feeble. Optically, it is negative (−). The double refraction is rather strong. The index of refraction varies from 1.5566 to 1.6005.

The lighter color usually serves to distinguish muscovite from both phlogopite and biotite.

Glauconite.—Glauconite is amorphous. It resembles earthy chlorite. It occurs as small globular masses and granular. H = 2; G = 2.2–2.4.

The composition varies much. It is essentially a hydrous silicate of iron and potassium with aluminum. In the closed tube it yields water. It fuses to a magnetic glass. Hydrochloric acid entirely decomposes some varieties, while it does not appreciably attack other varieties.

The luster is dull or glistening. The color is olive green, blackish green, yellowish green, and grayish green. Lamellar varieties are pleochroic. In lamellar aggregations it is biaxial. The index of refraction varies considerably, but is generally in the neighborhood of 1.61.

Topaz.—Topaz crystallizes in the orthorhombic system. The crystals are usually short prisms. It also occurs in columnar and granular forms. The cleavage parallel to (001) is highly perfect. The fracture is subconchoidal to uneven. H = 8; G = 3.4–3.65.

Topaz is $Al_2SiO_4(OF_2)$ with a variable amount of hydroxyl. It is infusible. Sulphuric acid only partially attacks it.

The luster is vitreous. The color is straw yellow, wine yellow, white, grayish, greenish, bluish, and reddish. The streak is uncolored. Thin sections are colorless. Optically, it is positive (+). The index of refraction runs from 1.6072 to 1.6375. The double refraction is low.

Topaz optically resembles andalusite. It can be distinguished from this mineral by the cleavage. Its lower double refraction distinguishes it from sillimanite. The index of refraction is higher than that of quartz and orthoclase.

Celestite.—Celestite crystallizes in the orthorhombic system. The crystals are commonly tabular or prismatic. It also occurs in fibrous and radiated, globular, and granular forms. The cleavage parallel to (001) is perfect. The fracture is uneven. H = 3–3.5; G = 3.95–3.97.

Celestite is strontium sulphate, $SrSO_4$. Small quantities of calcium are often present. Barium may also be present. It is fusible, and colors the flame the characteristic strontia red. The fused mass reacts alkaline. It is insoluble in acids.

The luster is vitreous, sometimes pearly. The streak is white. The color is white, faint bluish, and reddish. It is transparent to semitranslucent. Optically it is positive (+). The index of refraction runs from 1.61954 to 1.63697.

Prehnite.—Prehnite crystallizes in the orthorhombic system. It commonly occurs in groups of tabular crystals which are often barrel-shaped. It also occurs in globular, prismatic forms and in tabular or granular aggregations. The cleavage parallel to (001) is distinct. The fracture is uneven. H = 6 – 6.5; G = 2.80 – 2.95.

Prehnite is an acid orthosilicate of aluminum and calcium, $H_2Ca_2Al_2Si_3O_{12}$. In the closed tube it yields water. It fuses with intumescence. Hydrochloric acid slowly decomposes it without gelatinization.

The luster is vitreous, except on (001), where it is weak pearly. The color is light green, oil green, white, gray, and, in thin sections, colorless. The streak is uncolored. It is subtransparent to translucent. Optically, it is positive (+). The index of refraction is $\alpha = 1.616$, $\beta = 1.626$, $\gamma = 1.649$. The double refraction is strong. Prehnite resembles andalusite, topaz, and Wollastonite. Its higher double refraction distinguishes it from these minerals.

Tremolite.—Tremolite crystallizes in the monoclinic system. The usual forms are columnar and needles, the needles often in spherulitic aggregations. H = 5 – 6; G = 2.9 – 3.1.

Tremolite is a calcium magnesium amphibole, $CaMg_3(SiO_3)_4$. Ferrous iron replacing the magnesium may be sparingly present.

The color is white to dark gray, and colorless. Optically it is negative (–). The index of refraction is $\alpha = 1.6065$, $\beta = 1.6233$, $\gamma = 1.6340$.

Tremolite, in common with all monoclinic amphiboles, most closely resembles the monoclinic pyroxenes in its optical properties. The extinction angle of tremolite runs from 15° to 17°. The angle is larger in the case of the pyroxenes.

Wollastonite.—Wollastonite crystallizes in the monoclinic system. The forms are tabular and prismatic. The cleavage parallel to (100)

and (001) is perfect. The fracture is uneven. H = 4.5 − 5; G = 2.8 − 2.9.

Wollastonite is one of the pyroxenes. Chemically, it is a calcium metasilicate, $CaSiO_3$. It fuses easily on edges. Hydrochloric acid decomposes it, with the separation of gelatinous silica.

The luster is vitreous, and pearly on cleavage surfaces. The color is white, gray, yellow, red, brown, and colorless in thin sections. The streak is white. It is subtransparent to translucent. Optically it is negative (−). Occasionally it is optically positive (+), but this is rare. The index of refraction varies from 1.619 to 1.635. The acute bisectrix $X \wedge C = 32° 12'$. The double refraction is lower than that of epidote, and thus Wollastonite can be distinguished from that mineral. The double refraction is higher than that of Zoisite.

Anthophyllite.—Anthophyllite crystallizes in the orthorhombic system. The forms are commonly lamellar and fibrous. The cleavage parallel to (110) is perfect. H = 5.5 − 6; G = 3.1 − 3.2.

This is one of the amphibole group. Chemically it is a metasilicate of magnesium and iron. (Mg, Fe) SiO_3. It fuses with difficulty to a magnetic enamel. Acids do not act upon it.

The luster is vitreous, and, in cleavage faces, pearly. The color is brownish gray, yellowish brown, clove brown, brownish green, emerald green, sometimes metalloidal, and colorless in thin sections. The streak is uncolored or grayish. It is transparent to subtranslucent. It is pleochoric. Optically it is usually positive (+). The index of refraction varies from 1.6288 to 1.657.

Anthophyllite may be distinguished from the monoclinic amphiboles by its orthorhombic optical orientation and its colors.

Actinolite.—Actinolite crystallizes in the monoclinic system. It occurs in bladed crystals, columnar, fibrous, and granular massive. The common twinning plane is (100). The cleavage parallel to (110) is perfect. The fracture is subconchoidal. H = 5 − 6; G = 2.9 − 3.4.

This mineral is one of the amphiboles. The chemical composition is Ca $(Mg, Fe)_3$ $(SiO_3)_4$.

The color is bright green and grayish green. The pleochroism is distinct. Optically it is negative (−). The index of refraction is $\alpha = 1.611$, $\beta = 1.627$, $\gamma = 1.636$. The optical properties are very similar to those of tremolite.

Andalusite.—Andalusite crystallizes in the orthorhombic system. The form is usually prismatic. It also occurs massive, imperfectly columnar, radiated, and granular. The cleavage parallel to (110) is distinct. The fracture is uneven and subconchoidal. H = 7.5; G = 3.16 − 3.20.

Andalusite is Al_2SiO_5. A small percentage of iron may be present. It is infusible. Acids do not decompose it.

The luster is vitreous. The color is whitish, rose red, flesh red, violet, pearl gray, reddish brown, and olive green. The streak is uncolored. It is usually subtranslucent. In some colored varieties the pleochroism is strong. It is optically negative (−). The index of refraction is $\alpha=1.632$, $\beta=1.638$, $\gamma=1.643$.

Andalusite is distinguished from sillimanite by its optical orientation and by weaker double refraction, and from topaz by the cleavage and the character of the acute bisectrix.

Barite.—Barite crystallizes in the orthorhombic system. It occurs in granular and tabular forms. The cleavage parallel to (001) and (110) is perfect. The fracture is uneven. H = 2.5–3.5; G = 4.3–4.6.

Barite is barium sulphate, $BaSO_4$. Strontium, calcium, and, rarely, ammonium sulphate may be present. The barium flame coloration (green) is characteristic. It decrepitates and fuses. The fused mineral reacts alkaline. It is insoluble in acids.

The luster is vitreous and resinous, and on (001) pearly. The color is white, yellow, gray, blue, red, brown, dark brown, and colorless. The streak is white. It is transparent, translucent, and opaque. Optically it is positive (+). The index of refraction varies from 1.63344 to 1.65469. Barite is rare as a soil constituent.

Glaucophane.—Glaucophane crystallizes in the monoclinic system. The crystals are usually indistinctly prismatic. It also commonly occurs massive, fibrous, columnar, and granular. The fracture is conchoidal to uneven. H = 6–6.5; G = 3.103–3.113. This mineral belongs to the amphibole group. Chemically, it is $NaAl(SiO_3)_2$. $(Fe,Mg)SiO_3$.

The luster is vitreous to pearly. The color is azure blue, lavender blue, bluish black, and grayish. The streak is grayish blue. It is translucent. The pleochroism is rather strong. Optically, glaucophane is (−). The index of refraction varies from 1.6212 to 1.644. The extinction angle is about 5°.

The color and pleochroism of this mineral are distinctive.

Hornblende.—Hornblende crystallizes in the monoclinic system. It is generally prismatic. The prismatic angle is 124°. The cleavage parallel to (110) is highly perfect. The fracture is subconchoidal. H = 5–6; G = 2.9–3.4.

The chemical composition of hornblende is $Ca(Mg, Fe)_2(SiO_3)_3$, with $Na_2Al_2(SiO_3)_4$ and $(Mg, Fe)\ (Al, Fe)_2SiO_6$. Potassium, titanium, and rarely fluorine may be present.

The luster is vitreous, pearly on cleavage surfaces, and silky in the fibrous varieties. The color runs between black and white, though various shades of green, dark brown, yellow, pink, and rose red colors are also found. The streak is paler than the color, or else uncolored. It is usually subtranslucent to opaque. The colored varieties have

strongly marked pleochroism. Usually it is optically negative (−), but sometimes optically positive (+). The index of refraction varies from 1.629 to 1.6561.

Spodumene.—Spodumene crystallizes in the monoclinic system. It occurs in prismatic, massive, and cleavable forms. The cleavage is perfect parallel to (110). The fracture is uneven to subconchoidal. H = 6.5–7; G = 3.13–3.20.

Spodumene is a metasilicate of lithium and aluminum, $LiAl(SiO_3)_2$. A little sodium may be present. On heating, spodumene turns white and opaque, swells, and fuses. It gives the characteristic lithia flame reaction (purple red). Acids do not act upon it.

The luster is vitreous, and on cleavage surfaces pearly. The color is greenish white, grayish white, yellowish green, emerald green, yellow, amethystine purple, and colorless in thin sections. The streak is white. It is transparent to translucent. The deep green varieties are strongly pleochroic. It is optically positive (+). The index of refraction varies from 1.651 to 1.677.

Enstatite.—Enstatite crystallizes in the orthorhombic system. The habit is prismatic, massive, fibrous, or lamellar. The cleavage parallel to (110), (100), and (010) is pronounced. The fracture is uneven. H = 5.5; G = 3.1–3.3.

The chemical composition is variable. It may be, in pure enstatite, $MgSiO_3$, but iron is usually present and the formula may then become $(Mg, Fe)SiO_3$. It is almost infusible, the fusibility being 6. It is insoluble in hydrochloric acid.

The luster is pearly to vitreous. The color is grayish white, yellowish white, greenish white, olive green, and brown. The pleochroism is weak, but it becomes more marked in varieties richer in iron. The streak is uncolored or grayish. Enstatite is translucent to nearly opaque. Optically, it is positive (+). The index of refraction varies from 1.656 to 1.674. The extinction angle is parallel to the elongation.

The interference colors of all the orthorhombic pyroxenes, of which enstatite is a member, are lower than those of the monoclinic pyroxenes. In all longitudinal sections in enstatite the extinction is parallel to the *c* axis, whereas this is the case in the monoclinic pyroxenes only in the case of sections parallel to (100).

Sillimanite.—Sillimanite crystallizes in the orthorhombic system. This occurs in prismatic, fibrous, columnar, massive, and radiating forms. The cleavage parallel to (010) is perfect. The fracture is uneven. H = 6–7; G = 3.23–3.24.

The chemical composition is Al_2SiO_5. Acids do not attack it. The luster is vitreous to subadamantine. The color is hair brown, grayish brown, grayish white, grayish green, pale olive green, and colorless in thin sections. The streak is uncolored. It is transparent to

translucent. In some cases the pleochroism is distinct. Optically, sillimanite is positive (+). The double refraction is strong. The index of refraction runs from 1.657 to 1.6818.

Sillimanite differs from andalusite and zoisite by stronger double refraction and by having the prismatic axis Z in the direction of vibration of the slowest ray.

Olivine (Chrysolite).—Olivine crystallizes in the orthorhombic system. It usually occurs in grains. The cleavage parallel to (010) is sometimes distinct. The fracture is conchoidal. H = 6.5–7, G = 3.27–3.37.

Olivine is $(Mg, Fe)_2 SiO_4$. It is infusible in most cases. Hydrochloric and sulphuric acids decompose it with the separation of gelatinous silica.

The luster is vitreous. The color is olive-green, and sometimes brownish, grayish red, grayish green, yellowish brown, yellowish red. Thin sections are colorless. The streak is uncolored, or rarely yellowish. Olivine is transparent to translucent. Optically it is positive (+). The double refraction is strong. The index of refraction varies from 1.6535 to 1.7089.

Strontianite.—Strontianite crystallizes in the orthorhombic system. The crystals are often acicular. It also occurs in fibrous, granular, and columnar-globular forms. The cleavage parallel to (110) is nearly perfect. The fracture is uneven. H = 3.5–4; G = 3.68–3.714.

Chemically it is strontium carbonate, $SrCO_3$. Calcium may be present. Soluble in hydrochloric acid with effervesence.

The luster is vitreous, and resinous on uneven fracture faces. The color is pale asparagus green, apple green, white, gray, yellow, and yellowish brown. The streak is white. Strontianite is transparent to translucent. It is optically negative (−). The index of refraction runs from about 1.518 to 1.665.

The flame reaction (strontia) and effervescence with hydrochloric acid is usually enough to identify the mineral.

Datolite.—Datolite crystallizes in the monoclinic system. The habit of the crystals is not characteristic. It also occurs in grains, and in radially fibrous botryoidal and globular aggregations. The fracture is conchoidal to uneven. H = 5–5.5; G = 2.9–3.0.

Datolite is a basic orthosilicate of boron and calcium. $HCaBSiO_5$. In the closed tube, it gives much water. It fuses rather easily with intumescence, giving the flame a bright-green color. With hydrochloric acid it gelatinizes.

The luster is vitreous, and sometimes subresinous on fracture surfaces. The color is white, grayish, pale green, yellow, red, amethystine, dingy olive green, honey yellow, and colorless in thin sections. The streak is white. Datolite is transparent to translucent. Optically it is negative (—). The double refraction is strong. The index

of refraction is $\alpha = 1.6246$; $\beta = 1.6527$; $\gamma = 1.6694$. Datolite is distinguished from topaz, andalusite, wollastonite, and prehnite by its higher double refraction.

Diopside.—Diopside crystallizes in the monoclinic system. It occurs in short thick prisms, granular and fibrous. The angle between the prism faces is nearly 90°. The cleavage parallel to (110) is well developed. The fracture is uneven to conchoidal. H = 5–6; G = 3.2–3.38.

Diopside is a calcium magnesium pyroxene. The formula is $CaMg(SiO_3)_2$. When iron is present the formula may become $Ca(MgFe)(SiO_3)_2$.

The color is white, yellowish, grayish white, pale green, dark green, nearly black, and colorless. The luster is vitreous, inclining to resinous. Diopside is optically positive (+). The index of refraction varies from 1.6707 to 1.7271.

Witherite.—Witherite crystallizes in the orthorhombic system. The crystals are always repeated twins, which makes them simulate closely hexagonal pyramids. It also occurs in globular, tuberose, botryoidal, columnar, granular, and amorphous forms. The cleavage parallel to (010) is distinct. The fracture is uneven. H = 3–3.75; G = 4.29–4.35.

Witherite is barium carbonate, $BaCO_3$. It fuses and colors the flame yellowish green. The fused mass reacts alkaline. It is soluble, with effervescence, in dilute hydrochloric acid. Sulphuric acid added to the solution gives a white precipitate of barium sulphate, insoluble in acids.

The luster is vitreous, inclining to resinous on fracture surfaces. The color is white, yellowish, and grayish. The streak is white. Witherite is subtransparent to translucent. Optically it is negative, (−). The index of refraction runs from about 1.529 to 1.677.

The effervescence with hydrochloric acid and the barium flame reaction, taken together, are usually sufficient to identify the mineral.

Bronzite.—Bronzite is one of the orthorhombic pyroxenes. It is intermediate in composition between enstatite and hypersthene. The index of refraction is about 1.668. The luster is usually bronzelike. (See *Enstatite* and *Hypersthene.*)

Diallage.—Diallage crystallizes in the monoclinic system. It is usually characterized by a lamellar structure. It is intermediate in composition between *diopside and augite.* The index of refraction is about 1.68. (See *Diopside* and *Augite.*)

Aragonite.—Aragonite crystallizes in the orthorhombic system. The crystals are acicular, prismatic, often in stellate groups. It also occurs globular, fibrous, and compact aphanitic. The cleavage is distinct parallel to (010) and (110). The fracture is subconchoidal. H = 3.5–4; G = 2.93–2.95.

Aragonite is calcium carbonate, $CaCO_3$. Strontium, lead, and rarely zinc may be present. It effervesces and dissolves in acids. The general chemical reactions are very much the same as those of calcite.

The luster is vitreous, and resinous on fracture surfaces. The color is white, gray, yellow, green, and violet. The streak is uncolored. Aragonite is transparent to translucent. Optically it is negative (—). The index of refraction varies from 1.52749 to 1.71011. The double refraction is very strong.

Axinite.—Axinite crystallizes in the triclinic system. The crystals are usually broad and acute-edged. It may be lamellar or granular. The cleavage is distinct parallel to (010), (001), and $(1\bar{3}0)$. The fracture is conchoidal. H = 6.5–7; G = 3.271–3.294.

Axinite is a borosilicate of calcium and aluminum, $Ca_7Al_4B_2(SiO_4)_8$. The calcium may be partly replaced by manganese, iron, magnesium, and basic hydrogen. Ferric iron may also be present. It gives a pale-green color to the oxidizing flame. Acids do not decompose it, except when it has been previously ignited. Then it gelatinizes with hydrochloric acid.

The luster is highly glassy. The color is clove brown, plum blue, pearl gray, honey yellow, and greenish yellow. The streak is uncolored. It is transparent to subtranslucent. The pleochroism is strong. Optically it is negative (−). The index of refraction varies from 1.6720 to 1.6954. The double refraction is low.

Hypersthene.—Hypersthene crystallizes in the orthorhombic system. The habit is prismatic. The cleavage parallel to (110), (100), and (010) is pronounced. The fracture is uneven. H = 5–6; G = 3.40–3.50.

The chemical composition is $(Mg, Fe)SiO_3$. Alumina may sometimes be present. It fuses to a black enamel, magnetic when fused on charcoal. Hydrochloric acid partially decomposes it.

The luster is somewhat pearly on cleavage surfaces, and sometimes metalloidal. The color is dark brownish green, grayish black, greenish black, and pinchbeck brown. The streak is grayish and brownish gray. The pleochroism is rather strong. Hypersthene is translucent to nearly opaque. Optically it is negative (−). The index of refraction varies from 1.692 to 1.727. The double refraction is nearly as low as that of quartz.

The pleochroic colors of hypersthene, light red and green, are characteristic.

Zoisite.—Zoisite crystallizes in the orthorhombic system. It occurs prismatic, tabular, and fibrous. The cleavage parallel to (010) is perfect. The fracture is uneven to subconchoidal. H = 6–6.5; G = 3.25–3.37.

The chemical composition is $Ca_2(AlOH)Al_2(SiO_4)_3$. The aluminum may be replaced by iron. Manganese may also be present.

On heating it swells and fuses to a white blebby mass. When strongly heated it gives off water. Acids do not decompose it, except when it has been previously ignited; then it gelatinizes with hydrochloric acid.

The luster is vitreous; on cleavage faces pearly. The color is grayish white, gray, yellowish brown, greenish gray, apple green, peach-blossom red, rose red, and colorless in thin sections except when pleochroic. The streak is uncolored. Zoisite is transparent to subtranslucent. The pink varieties and thicker sections show pleochroism. Optically it is positive (+). The index of refraction varies from 1.696 to 1.7061. The double refraction is low.

Zoisite resembles epidote, but differs from it in being optically positive (+).

Arfvedsonite.—Arfvedsonite crystallizes in the monoclinic system. The crystal habit is prismatic. The cleavage is prismatic, perfect. The fracture is uneven. H = 6; G–3.44 – 3.45.

Arfvedsonite is a slightly basic metasilicate of sodium, calcium, and ferrous iron, chiefly. Aluminum, ferric iron, manganese, magnesium, and potassium may be present. It fuses with intumescence to a magnetic globule. It gives the yellow (soda) flame coloration. Acids do not act upon it.

The luster is vitreous. The color is pure black. Thin scales are deep green. The streak is a deep bluish gray. Except in thin splinters, it is opaque. The pleochroism is strong. The optical character is uncertain. The extinction angle is about 14°. The index of refraction runs from about 1.687 to 1.708.

Augite.—Augite crystallizes in the monoclinic system. It occurs in prismatic and granular forms. The cleavage parallel to (110) is sometimes rather perfect. The fracture is uneven to conchoidal. H = 5–6; G = 3.2–3.6.

The chemical composition of augite is pretty complex. It may be formulated as m $Ca(Mg,Fe)(SiO_3)_2$, n $(Mg,Fe)(Al,Fe)_2(Si,Ti)O_6$, with sometimes $Na(Al,Fe)(SiO_3)_2$. The fusibility is 3. Acids do not act upon it.

The color is dark green to black; and in thin sections colorless to pale green. The index of refraction varies from 1.6975 to 1.74. Augite is optically positive (+).

Cyanite (Disthene).—Cyanite crystallizes in the triclinic system. The crystals are usually long-bladed forms. The cleavage parallel to (100) is very perfect. The hardness varies in different parts of the crystal. It is generally somewhere between 4 and 7. G = 3.56–3.67.

Cyanite is Al_2SiO_5. It is infusible. Acids do not decompose it.

The luster is vitreous to pearly. The color is blue and white. Often the margin of the crystal is white, while the middle of it is blue. Gray, green, and black colors also occur. Thin sections are

colorless, light blue, or greenish blue. The pleochroism is weak. The streak is uncolored. Cyanite is translucent to transparent. Optically it is negative (−). The index of refraction runs from 1.712 to 1.729. The double refraction is low.

Chloritoid (*Ottrelite*).—This mineral is monoclinic or triclinic (?). It is usually coarsely foliated, massive, and in thin scales. The cleavage is basal, though not as perfect as in the case of the micas. H = 6.5; G = 3.52–3.57.

Chloritoid is $H_2(Fe,Mg)Al_2SiO_7$. Manganese is present in the variety ottrelite. Heated, it yields water. It is nearly infusible. Hydrochloric acid does not decompose it, but it is completely decomposed by sulphuric acid.

The color is dark gray, greenish gray, greenish black, grayish black, and in very thin plates grass green. The streak is uncolored, grayish, or slightly greenish. Cleavage surfaces have a somewhat pearly luster. The pleochroism is strong. The double refraction is feeble. It is optically positive (+). The index of refraction varies from 1.741 to 1.77.

Staurolite.—Staurolite crystallizes in the orthorhombic system. The form is prismatic. It is commonly found as cruciform twins. The cleavage parallel to (010) is distinct, but interrupted. The fracture is subconchoidal. H = 7 − 7.5; G = 3.65 − 3.75.

The formula of staurolite is doubtful. It is usually written $2H_2O.6(Fe,Mg)O.12Al_2O_3.11SiO_2$(?). Groth has suggested the formula, $HFeAl_5Si_2O_{13}$. Excepting the manganesian variety, which fuses easily to a black magnetic glass, staurolite is infusible. Sulphuric acid decomposes it imperfectly. The luster is subvitreous to resinous. The color is dark reddish brown, brownish black, and yellowish brown. Thin sections are yellow to red brown. The pleochroism is distinct. Optically, it is positive (+). The index of refraction is $\alpha = 1.736$, $\beta = 1.741$, $\gamma = 1.746$.

Epidote.—Epidote crystallizes in the monoclinic system. It occurs in prismatic, fibrous, and granular forms. The cleavage parallel to (001) is perfect. The fracture is uneven. H = 6.7; G = 3.25 − 3.5.

Epidote is a basic orthosilicate of calcium, aluminium, and iron, $Ca_2(AlOH)(Al,Fe)_2(SiO_4)_3$. It gives water in the closed tube on strong ignition. It fuses with intumescence to a dark-brown or black mass. Hydrochloric acid partially decomposes it, but it gelatinizes with hydrochloric acid after ignition.

The luster is vitreous, inclining to resinous or pearly. The color is pistachio green, yellowish green, brownish green, greenish black, black, clear red, yellow, gray, grayish white, and rarely colorless. The streak is uncolored or grayish. Epidote is transparent to opaque. The pleochroism is strong. The double refraction is very strong. Optically it is negative (−). The index of refraction varies from 1.7238 to 1.7677.

Monazite.—Monazite crystallizes in the monoclinic system. It generally occurs in grains. The fracture is conchoidal to uneven. H = 5 – 5.5; G = 4.9 – 5.3.

Monazite is a phosphate of the cerium metals, cerium, lanthanum, and didymium $(Ce,La,Di)PO_4$. Thoria and silica are usually present. It is infusible, but turns gray. Moistened with sulphuric acid, it colors the flame bluish green. It is soluble in hydrochloric acid with difficulty.

The luster inclines to resinous. The color is hyacinth red, clove brown, reddish brown, yellowish brown, and colorless to yellowish in thin sections. Monazite is subtransparent to subtranslucent. It is optically positive (+). The index of refraction runs from 1.7863 to 1.8411.

The refraction and double refraction are characteristic.

Acmite.—Acmite crystallizes in the monoclinic system. The crystals are long prismatic. The cleavage parallel to (110) is distinct. The fracture is uneven. H = 6 – 6.5; G = 3.50 – 3.55.

Acmite is $NaFe(SiO_3)_2$. Ferrous iron may also be present. Acmite fuses rather easily to a black magnetic globule. It colors the flame deep yellow. Acids act upon it slightly.

The luster is vitreous, inclining to resinous. The color is brownish, reddish brown, green, blackish green. The streak is pale yellowish gray. This mineral is subtransparent to opaque. Optically, it is negative (–). The index of refraction is about 1.80.

Aegirine.—The color is greenish black. (See *Acmite* above.)

Titanite.—Titanite crystallizes in the monoclinic system. The crystals are often wedge shaped and flattened. It also occurs in massive, granular, and compact forms. The cleavage parallel to (110) is rather distinct. H = 5 – 5.5; G = 3.4 – 3.56.

Titanite is $CaTiSiO_5$. Iron, manganese, and yttrium may be present. It is imperfectly soluble in hydrochloric acid.

Sulphuric and hydrofluoric acids completely decompose it.

The luster is adamantine to resinous. The color is brown, gray, yellow, green, rose red, and black. The pleochroism is distinct in the deeply colored varieties. The streak is white. Titanite is transparent to opaque. Optically, it is positive (+). The index of refraction varies from 1.8839 to 2.0232. The double refraction is very high in some directions, but very low in others (normal to Z).

Limonite.—See *Limonite* under *Opaque minerals.*

CONCLUSION.

In the foregoing descriptive list those minerals have been described with which the soil mineralogist may, in one soil or another, have occasion to deal. It is not probable that all of these minerals will be found in any one soil; and it is possible that in certain soils minerals not included in the list may be found. Indeed, it is probable that all

mineral species known to mineralogy do occur occasionally as soil constituents. But the vast majority of them, if found at all, would be found only as exceptional ingredients, and most of them only under exceptional conditions. But it is believed that the list includes all minerals that will be found ordinarily, as well as a few that occur only under exceptional circumstances. For instance, leucite, on account of its easy decomposition, as well as its origin, would not be expected to be found as a usual soil constituent, although it might be a very common soil constituent in soils from the Leucite Hills and similar localities. The same would apply to such minerals as celestite, strontianite, barite, and the soluble sulphates and chlorides which usually occur in alkali districts.

As a general maxim, upheld by the experience of this Bureau, it may be stated that "practically every soil contains all the common rock-forming minerals."[1] Of course, opinions as to what minerals are common rock-forming minerals vary. But every petrographer would agree as to certain species being included under the term. The number of minerals to be found in the sand and silt separates of every soil is surprisingly large, and doubtless an even greater number would be found in the clays. But as yet the limitations of the microscope prohibit the satisfactory examination of these latter.

A complete census of the soil minerals can scarcely be said to be advisable for practical work. On account of the large number of minerals to be located and determined a large amount of time is unnecessarily wasted. It is generally best to determine only the more abundant species and a few of the rarer ones belonging to distinct mineral groups. Unless ultimate work is desired, it is unnecessary to differentiate such groups as, for example, the chlorites.

In conclusion, it may be stated that any mineral commonly occurring in rocks may be expected in soils, no matter what the origin of the particular soil may be.

A large number of soils have now been examined in this laboratory as well as in other laboratories, mainly abroad, and the results have been or are to be published in other connections, so that it does not seem wise to recapitulate them here. Work is now in progress with the distinct end in view to determine the extent of the mineral complexity of the more prominent American soil types, and it is expected that the results will be collected and published for the use of other investigators at an early date.

To aid in the rapid identification of soil minerals, Tables IX, X, XI, and XII (96 et seq.) have been added in which the minerals are arranged primarily according to the classification adopted in the foregoing description, and secondarily according to their refractive indices. Other physical properties which may be of use in their determination are also stated.

[1] Bul. No. 30, Bureau of Soils, U. S. Dept. of Agr.; Cameron, F. K., The Soil Solution, Easton, Pa., 1911.

TABLE IX.—*Opaque minerals.*

[Do not permit the passage of transmitted light; appear black in transmitted light (the stage is shaded to shut out all the reflected rays).]

Color in reflected light.	Streak.	Hardness.	Specific gravity.	Remarks.	Mineral.
Black	Black	5.5–6.5	5.1	Magnetic; widely distributed in soils and rocks	Magnetite, Fe_3O_4.
Do	Black to brown	5–6	4.5–5.0	Feebly magnetic at times	Ilmenite, $Fe(TiFe)O_3$.
Do	Black	1–2	2.2	In laminæ	Graphite, C.
Brownish black	Dark brown	5.5	4.3–4.6	Translucent on thin edges, with dark-brown color. Index, 2.09.	Chromite, $FeCr_2O_4$.
Pale brass yellow	Brownish black	6–6.5	4.9–5.1		Pyrite, FeS_2.
Black to red or yellow	Red	5.5–6.5	4.9–5.3		Hematite, Fe_2O_3.
Red to yellow	Yellow	5–5.5	3.6–4.0	Common pigment of soils; as a coating on soil grains, and often forms a large part of the clay particles.	Limonite, $2Fe_2O_3.3H_2O$.
Brown to black	Gray	Soft.	2.5	Characterized by irregular outline and rather fibrous texture; disappears upon ignition.	Humus or organic matter.

TABLE X.—*Isotropic minerals.*

[When viewed between crossed nicols these minerals do not permit the passage of light. The field and grain remain uniformly dark in a rotation of the stage through 360°. In convergent polarized light the mineral does not show any interference figure—distinction from basal sections of uniaxial minerals. Very weak birefringence is revealed by the use of a quartz or selenite plate, showing the sensitive tint (between crossed nicols). It is desirable to examine such a mineral in a different orientation before deciding that the mineral is isotropic. This is accomplished by moving the cover glass by pressing on an edge. Thereby the minerals readjust themselves to new conditions often showing different orientations.]

Index.	Color.	Specific gravity.	Hardness.	Remarks.	Mineral.
1.43	Colorless, also green and purplish.	3.18	4		Fluorite, CaF_2.
1.45 (about)	Varied; often red or brown	1.9–2.3	5.5–6.5	Sometimes birefringent with aggregate polarization; contains iron oxide as inclusions, also fluid and gas pores.	Opal, SiO_2nH_2O.
1.48–1.63	Generally colorless	2.2–2.4	Varied.	Volcanic ash, from lava and effusive rocks; often characterized by minute inclusions—liquids and microlites; also gas pores; indices vary with content of SiO_2.	Glass; chemical composition varies.
1.48	Colorless or blue	2.1–2.3	5.5	Rare; at times optically anomalous	Sodalite, $3NaAlSiO_4+NaCl$.
1.49	Colorless, yellowish, reddish	2.22–2.29	5.5	Often shows anomalous birefringence	Analcite, $NaAlSi_2O_6H_2O$.
1.49	Colorless, also faint blue	2.2–2.4	5.5	Optically anomalous	Noselite, $3NaAlSiO_4Na_2SO_4$.
1.50	Colorless, often blue	2.4–2.5		Shows zonal growth or deposition of impurities	Hauyn, $3NaAlSiO_4(Na_2Ca)SO_4$.
1.51	Colorless	2.5	5.5–6	With a sensitive plate shows anomalous birefringence and twinning; regular arrangement of inclusions.	Leucite, $KAlSi_2O_6$.
1.72	Colorless, also greenish and brownish.	3.6–3.7	7.5–8	Distinguished from garnet by the absence of SiO_2 and the difference in indices of refraction.	Spinel, $MgO.Al_2O_3$.
1.74–1.76	Colorless, yellowish, brownish.	3.4–3.6	7–7.5	In grains; sometimes has anomalous birefringence (0.002); lime garnet.	Grossularite, $Ca_3Al_2(SiO_4)_3$.

1.81	Red	3.8–4.3	7–7.5	In grains; manganese garnet	Spessartite, $Mn_3Al_2(SiO_4)_3$.
1.81	Dark red	4.1–4.3	7–7.5	In grains; a common variety of garnet	Almandite, $Fe_3Al_2(SiO_4)_3$.
1.75	Red	3.7–3.8	7–7.5	In grains; gem garnet; distinguished by color and index	Pyrope, $Mg_3Al_2(SiO_4)_3$.
2.1	Brownish black; brown on thin edges.	4.3–4.6	5.5	Granular	Chromite, $FeOCr_2O_3$.
2.38	Yellowish to brown	4	5.5	In grains; characterized by its color and weak birefringence.	Perovskite, $CaTiO_3$.

TABLE XI.—*Anisotropic minerals—Uniaxial.*

[Minerals in this group are distinguished from isotropic minerals in that they transmit light between crossed nicols and from biaxial minerals in that they show in convergent polarized light the emergence of a uniaxial interference figure. Minerals of this group have parallel extinction distinguishing them from some of the biaxial minerals, particularly those of the monoclinic and triclinic systems. Hexagonal minerals having rhombohedral cleavage (calcite, etc.) apparently show inclined extinction on the cleavage face. This, however, must not be measured from the rhombohedral edges, since these are not coincident with the direction of the crystallographic axes. The direction of extinction bisects the plane angle of the rhombohedral face. The direction of elongation is generally that of the crystallographic axis *c*, also the direction of the optic axis; therefore the optical character of the elongation is the same as the optical character of the mineral. The vibration direction of the ordinary ray (ω) is at right angles to this elongation. The index of refraction of the extraordinary ray (ϵ) is independent of the orientation of the grain; therefore its determination is used in column 1 to distinguish the mineral. The index of the other ray varies with the orientation of the grain, but in the table its maximum deviation from the value of the ordinary ray is used as a diagnostic. As the value of the extraordinary ray is less than or greater than that of the ordinary ray (— or +, respectively), it has very important diagnostic value. The determination of the birefringence may be readily determined from the Michel-Levy table, as outlined on page 30.]

Index.	Crystal system.	Cleavage.	Hardness.	Specific gravity.	Color.	Pleochroism.	Indices of refraction. ω.	Indices of refraction. ϵ.	Birefringence.	Optical character.	Remarks.	Mineral.
1.48+.0...	III	.....	7	2.3	Colorless	.....	1.477	.....	0.002	+	Hexagonal plates; rare	Tridymite, SiO_2.
1.49—.0...	III	(10$\bar{1}$1)	4–5	2.1	.....do.....	.....	n=	1.485	.003	±	A zeolite; at times biaxial or nearly so.	Chabazite, $CaNa_2Al_2Si_4O_{12}.6H_2O$.
1.53—.03.	III	(1010) (p); (11$\bar{2}$0) (imp)	5–6	2.5	Colorless, yellowish, brownish.	.....	1.524	1.496	.028	—	Prisms, needles, grains	Cancrinite, $H_6Na_6Ca(NaCO_3)_2Al_8(SiO_4)_9$.
1.54—.0..	II	(001)	4.5–5	2.4	Colorless	.....	1.537	1.535	.002	±	A zeolite; rare	Apophyllite, $H_7KCa_4(SiO_3)_8+4\frac{1}{2}H_2O$.
1.54—.01.	III	(10$\bar{1}$0) (poor)	5.5–6	2.6	.....do.....	.....	1.539	1.534	.005	—	Distinguished by its index and low birefringence; sometimes has an anomalous 2 E; comparatively rare.	Nepheline, $NaAlSiO_4$.
1.54+.01.	III	.....	7	2.65	Colorless; at times variously colored	.....	1.544	1.553	.009	+	In irregular grains.	Quartz, SiO_2.
1.58—.02.	II	(001) (p)	5–6	2.68	Colorless; bluish, reddish.	.....	1.583 1.563	1.553 1.545	.030 to .018	—	In grains; a scapolite; distinguished by uniaxial character, birefringence, and optical character.	Wernerite; composition varies between Me_3Ma_1 and Me_1Ma_2 where $Me=Ca_4Al_6Si_6O_{25}$, $Ma=Na_4Al_3Si_9O_{24}Cl$.
1.58—.01.	III	(0001) (imp)	7.5–8	2.7	Colorless; green, blue, yellow.	.....	1.579	1.574	.005	—	.....	Beryl, $Be_3Al_2(SiO_3)_6$.

TABLE XI.—*Anisotropic minerals—Uniaxial*—Continued.

Index.	Crystal system.	Cleavage.	Hardness.	Specific gravity.	Color.	Pleochroism.	Indices of refraction.		Birefringence.	Optical character.	Remarks.	Mineral.
							ω.	ϵ.				
1.64—.02.	III	.....	7	3.0–3.24	Generally colored.	Absorption of the ordinary ray.	1.632 1.685	1.612 1.652	.017 to .034	—	Prismatic; indices vary with composition; absorption of the ordinary ray, characteristic.	Tourmaline; complex boro-silicate of sodium magnesium, iron, and aluminum.
1.64—.00.	III	(0001) (imp)	5	3.1–3.2	Colorless; sometimes colored.	.....	1.638	1.634	.004	—	Prismatic; also in grains; characterized by high index and low birefringence.	Apatite, $Ca_4(CaF)(PO_4)_3$. Cl replaces F.
1.66—.17	III	(1011) (p)	3	2.6–2.8; 2.71 pure	Colorless	.....	1.658	1.486	.172	—	Granular; characterized by a high birefringence and uniaxial nature.	Calcite, $CaCO_3$.
1.68—.18.	III	(1011) (p)	3.5–4	2.85–2.95	.....do.....	.....	1.682	1.503	.179	—	Much like calcite; crystals frequently have rounded faces and edges; lacks polysynthetic twinning as in calcite, only very slowly soluble in cold dilute HCl.	Dolomite $(CaMg)CO_3$.
1.77—.01.	III	.....	9	3.9–4.1	Colorless; blue, red.	Blue or red; sea green, yellow, greenish-yellow.	1.769	1.760	.009	—	In grains.....	Corundum, Al_2O_3.
1.93+.05.	II	(110) (imp)	7.5	4.2–4.8	Colorless, sometimes colored.	.....	1.931	1.993	.052	+	In tetragonal prisms, usually terminated with pyramids.	Zircon, $ZrSiO_4$.
1.83—.20.	III	(1011)	3.5–4	3.94	Colorless; at times colored	.....	1.873	1.633	.240	—	Similar to calcite; both indices high; insoluble in cold dilute HCl.	Siderite, $FeCO_3$.
2.55—.06.	II	(001)-(111)	5.5–6	3.9	Brown to green	Weak; deep blue, bright blue, orange, yellow.	2.562	2.489	.073	—	Tabular, prismatic; rare...	Anatase or Octahedrite, TiO_2.
2.62+.28.	II	(100)-(110)	6.–6.5	4.2	Red, brown, yellowish; at times bluish or green.	Yellow to brownish, brown-yellow to yellow green.	2.616	2.903	.287	+	Tetragonal prisms, sometimes twinned, characterized by high index, high birefringence, and reddish-brown or yellow color.	Rutile, TiO_2.
3.22—.3.	III	.....	5.5–6.5	4.9–5.3	Dark red.....	Brownish-red; bright yellow-red.	3.22	2.94	.28	—	Distinguished by red color in reflected light; generally opaque.	Hematite, Fe_2O_3.

1. V = 62° .....

1. V = 27° .....

2. V = large .....

[2] Basaltic.

[Minerals of this subdivision are characterized by their anisotropic and biaxial nature. All such minerals transmit light between crossed nicols and extinguish four times in a rotation of the stage through 360°, except those which show the emergence of an optic axis, see page 24. The birefringence varies with the orientation of the grain and with the thickness, therefore, its determination must be associated with the orientation, see page 30. The optical character of the mineral can be determined from any section after the orientation has been discovered in convergent polarized light. Orthorhombic minerals, and monoclinic minerals in the zone of symetry (normal to 010), have parallel extinction. Monoclinic minerals in any other orientation and triclinic minerals show inclined extinction. The value of the retarded indices as determined under the microscope will vary with the orientation of the grain, therefore the proper assignment in the tables of minerals with high birefringence will be somewhat difficult. The various indices must be associated with the proper orientation, thus an index of 1.589 may be the index α, β, or γ, owing to the vibration in the axes of elasticity, a, b, or c, respectively. The assignment of the indices to the vibration directions are very important diagnostics to the identification of the mineral. The optical character, the optical nature of the elongation, and the other optical data are also essential to the proper assignment of the mineral in the tables.]

Index.	Crystal system.	Cleavage.	Hardness.	Specific gravity.	Color.	Pleochroism.	Orientation.	Indices. α	Indices. β	Indices. γ	Birefringence. $\gamma-\alpha$	Birefringence. $\gamma-\beta$	Elongation. Direction.	Elongation. Nature.	Optic angle	Character.	Remarks.	Mineral.
1.48+0.01	IV	110	5–5.5	2–2.2	Colorless; yellowish, reddish		$a=a$ $c=c$	1.477	1.480	1.489	0.012	0.009	$\parallel c$	+	2V=60°	+	A zeolite; distinguished from scolecite by index and the optical nature of elongation.	Natrolite, $(Na_2Al_2Si_3O_{10}+2H_2O$.
1.51–1.57 (varies)	V	001 (p)–010	4–4.5	2.2	Colorless		$b=a$ $a:c=11$ to 18°		1.51–1.57		.003		$\parallel a$	+	2V large	+	A zeolite	Phillipsite, $(K_2Ca)Al_2(SiO_3)_4+4\frac{1}{2}H_2O$.
1.49–0.0	Pseudo III	101–1	4–5	2.1	do		$B\times a\perp .0001$		1.485		.003				2E small; at times uniaxial	±	At times uniaxial or nearly so	Chabazite, $(Ca,Na_2)Al_2(SiO_3)_4+6H_2O$.
1.50–0.01	V	010 (p)	3.5–4	2.2	Colorless; reddish		$b=c$ $a=a$ (nearly)	1.498	1.499	1.505	.007	.006	$\parallel b$	+	2E=52°	+	Plates and tables; a zeolite	Heulandite, $H_4CaAl_2(SiO_3)_6+3H_2O$.
1.50–0.01	V	110	5–5.5	2.2–2.4	Colorless		$b=b$ $c:c=17°$	1.512	1.518	1.519	.007	.001	$\parallel c$	–	2E=55°	–	A zeolite	Scolecite, $CaAl_2Si_3O_{10}+3H_2O$.
1.52–0.01	V	010–110	3.5–4	2.3	Colorless; at times yellowish		$b=b$ $c:c=+20°$	1.513	1.524	1.525	.012	.001	$\parallel c$	–	2E=51°	–	do	Laumontite, $H_4CaAl_2Si_4O_{14}+2H_2O$.
1.52–0.01	V	010 (p)–100 (p)–111	1.5–2	2.2–2.5	Colorless		$b=b$ $c:c=-53°$	1.520	1.523	1.530	.010	.007	$\parallel 010$	–	2V=58°	+		Gypsum, $CaSO_4+2H_2O$.
1.52+0.01	V	001 (p)–010 (good)	6	2.55–2.58	Colorless; yellowish, pinkish		$b=c$ $a:a=+5°$	1.519	1.523	1.525	.006	.002	$\parallel a-$ $\parallel c\pm$	– ±	2V=69°	–	Tables, rods, and grains; easily distinguished by the indices of refraction, sometimes shows Carlsbad twinning; widely distributed in soils.	Orthoclase, $KAlSi_3O_8$.
1.52+0.01	VI	001 (p)–010 (good)	6–6.5	2.54–2.57	White, yellowish, greenish, reddish			1.522	1.526	1.530	.008	.004	$\parallel 010$		2V=large	–	Characterized by polysynthetic twinning, which gives rise to peculiar lattice-work effect when viewed between crossed nicols; widely distributed in soils.	Microcline, $KAlSi_3O_8$.
1.54–.01	VI	001 (p)–010 distinct	6–6.5	2.62	Colorless			1.529	1.532	1.539	010	.007			2V=77–84°	+	Basal cleavage most prominent, therefore the grains are generally flat and show polysynthetic (albite) twinning.	Albite, $NaAlSi_3O_8$.
1.54–.01	IV	010	2–3	2.4–5	Greenish, colorless, yellowish		$b=a$ $c=c$		1.54		.013		$\parallel c$	+	2E=32°	+	Fibrous serpentine	Chrysolite, $H_4Mg_3Si_2O_9$.
1.55	V	001 (p)	2–2.5	2.62	Colorless		$b=c$ $c:a=+20°$		1.55		.007		$\parallel c$	+	2V=90°	–	A common alteration product of the feldspar and other alumino-silicates; generally present in aggregates, often stained with oxide of iron; constitutes the greater part of the "clay" separate of the soil.	Kaolin, $H_4Al_2Si_2O_9$.
1.55–.01	IV	010 (imp)	7–7.5	2.65	Colorless; blue, violet	Lacking, or very weak	$b=c$ $c=a$	1.535	1.540	1.544	.009	.004	$\parallel c$	–	2V=39–84°	–	Rare	Cordierite (iolite), $H_2(Mg,Fe)_2Al_3Si_5O_{18}$.
1.54–.01	IV		7	2.59–2.64	Colorless; yellowish, brownish		$c=a$	1.533	1.538	1.544	.011	.006				–	Often stained with iron oxide	Chalcedony, essentially SiO_2.
1.55–.01	VI	001 (p)–010	6	2.63–2.67	Colorless; at times colored			1.540	1.544	1.547	.007	.004			2V=90–93°	–	Plagioclase, most readily distinguished from the other plagioclases by indices of refraction.	Oligoclase, Ab_3An_1.
1.55+.01	VI	001 (p)–010	5–6	2.67–2.68	do			1.549	1.551	1.555	.006	.004			2V=90–80°	+	Plagioclase; distinguished from the other plagioclases by indices of refraction; shows polysynthetic twinning.	Andesine, Ab_3An_2 to Ab_1An_1.
1.55+.01	VI	001 (p)–010	5–6	2.69–2.72	do			1.555	1.558	1.563	.008	.005			2V=80–75°	+	Plagioclase; shows polysynthetic twinning on the (001) face and the zone normal to 010; distinguished from the other plagioclases by indices of refraction.	Labradorite, Ab_1An_1 to Ab_1An_2.
1.57–.01	IV	010 (p)	3–4	2.57–2.8	Greenish, yellowish, colorless		$a=a$ $b=c$	1.569	1.570	1.571	.011	.001	$\parallel 101$	+	2E=110°	–	Plates and disks; forms a platy aggregate not easily distinguished from chlorite.	Antigorite, $H_4Mg_3Si_2O_9$.
1.57+.04	IV	001 (p)–010 (p)–100 (less p)	3–3.5	2.9–3	Colorless		$b=c$ $c=a$	1.570	1.576	1.614	.044	.038	$\parallel c$	–	2E=71°	+	Grains; sometimes in rods or fibers; rare	Anhydrite, $CaSO_4$.
1.59–.05	V	001 (p)	1	2.7–2.8	do		$b=c$ $c=a$	1.559	1.569	1.580	.050	.000	$\parallel c$	+	2E=6–40°	–		Talc, $H_2Mg_3Si_4O_{12}$.
1.58+0.05	V	010 (p)	1.5–2	2.6–2.7	Colorless or blue		$b=a$ $c:c=62°$	1.577	1.605	1.627	.050	.022	$\parallel c$		2E=143°	+	Prismatic to fibrous	Vivianite, $Fe_3(PO_4)_2+8H_2O$.
1.59–0.02	VI	001 (p)–010 (less p)	6–6.5	2.73–2.76	Colorless			1.575	1.584	1.588	.013	.004	$\parallel a$ $\parallel c$	– ±	2V=75–78°	–	A plagioclase; distinguished from the other plagioclases by indices of refraction.	Anorthite, $CaAl_2Si_2O_8$.
1.59–0.02	V	001	1–1.5	2.8–2.9	Colorless, green, yellow				1.58		.041		$\parallel c$	+	2V=62°	–	In lamellar, foliated masses, also radiated or fibrous, also compact. Rare.	Pyrophyllite, $H_2Al_2Si_4O_{12}$.
1.59+0.01	V	001 (p)	2–2.5	2.6–2.8	Green	a and b, green; c, yellow	$b=b$ $c:c=-2°–9°$	1.585	1.586	1.596	.011	010	$\parallel c$	–	2V=32°–90°	±	Often shows anomalous interference color (blue-gray) and no extinction, owing to its high dispersion; penninite acts as a uniaxial mineral with the emergence of the optic axis on the cleavage face (001); in clinochlor the optic angle varies and the acute bisectrix is inclined to the cleavage face (001), which makes the extinction inclined in the zone normal to this face.	Chlorite, $H_8(Mg,Fe)_5Al_2Si_3O_{18}$: penninite; clinochlor.
1.60–0.03 (varies)	V	001 (p)	2.5–3	2.7–3.1	Dark brown to green	b and c brown or green; a yellow.	$b=b$	1.577	1.589	1.597	.020	.008	$\parallel c$	+	2E=0–30°	–	Occurs in flat plates which show but faint birefringence and almost uniaxial interference figure.	Biotite, $(K,H)_2(Mg,Fe)_3(Al,Fe)_2(SiO_4)_3$.
1.60–0.03	V	001 (p)	2.5–3	2.8–2.9	Colorless, yellowish, greenish		$Bx\alpha\perp 001$		1.60		High.		$\parallel c$	+	2E=60°	–	A soda muscovite; distinguished from muscovite and talc microchemically. Rare.	Paragonite, $H_2(Na,K)Al_3(SiO_4)_3$.
1.60+0.03	V	100 (p)–001 (p)	4.5–5	2.74–2.88	Colorless		$b=c$		1.61		.038		$\parallel b$	+	2V=60°	+	Generally in needles or fibers.	Pectolite, $NaHCa_2Si_3O_9$.
1.61–0.05 (varies)	V	001 (p)	2.5–3	2.78–2.85	Brownish, reddish	a Colorless; b and c brownish yellow.	$c=a$	1.562	1.626	1.606	.044	.020	$\parallel c$	+	2E=0–30°	–	Similar to biotite with micaceous cleavage; interference figure nearly uniaxial.	Phlogopite, $H_2(K,H)_2(MgF)_2Mg_3Al(SiO_4)_3$.
1.60–0.04	V	001 (p)	2.5–3	2.76–3	Colorless		$c=a$	1.561	1.598	1.601	.038	.003	$\parallel c$	+	2E=60–70°	–	Tabular with micaceous cleavage as with biotite and phlogopite.	Muscovite, $H_2KAl_3(SiO_4)_3$.
1.61 (varies)		001	2	2.2–2.4	Green to yellow					1.61		.020			2E=0–40°	–	Consisting of rounded grains, showing aggregate polarization.	Glauconite, $KFe(SiO_3)_2+nH_2O$.
1.62+0.01	IV	001 (p)	8	3.4–3.7	Colorless		$a=a$ $c=c$	1.619	1.622	1.628	.009	.006	$\parallel c$	+	2E=89–129°	+	In prisms	Topaz, $Al_2SiO_4(F,OH)_2$.
1.62+0.01	IV	001	3–3.5	3.96	Colorless, greenish		$a=c$ $a=a$	1.622	1.623	1.631	.009	.008	$\parallel c$	+	2V=51°	+	Rare	Celestite, $SrSO_4$.
1.62+0.01	IV	001	6–6.5	2.8–2.95	do		$a=a$ $c=c$	1.616	1.626	1.649	.033	.023	$\parallel c$	+	2E=123°	+	do	Prehnite, $H_2Ca_2Al_2Si_3O_{12}$.
1.63–.03	V	(110)	5–6	2.9–3.1	Colorless		$b=b$ $c:c=+16°$	1.609	1.623	1.635	.026	.012	$\parallel c$	+	2V=85°	–	An amphibole; ordinarily occurs in elongated columns, also in needles. The needles are often parts of spherulitic aggregates.	Tremolite, $Ca_2Mg_5(SiO_3)_8$.
1.63–.01	V	100 (p)–001 (p)–101 (imp)	4.5–5	2.8–2.9	do		$b=b$ $c:a=-32°$	1.621	1.633	1.635	.014	.002	$\parallel b$	±	2E=70°	–	Forms rodlike to tabular crystals; rare; a pyroxene	Wollastonite, $CaSiO_3$.
1.63+.03	IV	100 (p)–110 (imp)	5.5–6	3.1–3.2	Colorless, brownish, greenish		$a=a$ $c=c$	1.133	1.642	1.657	.024	.015	$\parallel c$	+	2V=84°	+	An amphibole	Anthophyllite $(MgFe)\,SiO_3$.
1.64–.03	V	110 (p)	5–6	3–3.2	Pale to dark green		$b=b$ $c:c=+15°$	1.611	1.627	1.636	.025	.009	$\parallel c$	+	2V=78°	–	Similar to tremolite in optical properties and occurrence; an amphibole.	Actinolite, $Ca(MgFe)_5(SiO_3)_8$.
1.64–.01	IV	110	7	3.1–3.2	Reddish; at times colorless	a, rose red; b and c, colorless.	$a=c$ $b=b$	1.632	1.638	1.643	.011	.005	$\parallel c$	–	2V=84°	–	Prismatic, generally flat	Andalusite, Al_2SiO_5.
1.64+.01	IV	001 (p)–110 (p)	2.5–3.5	4.3–4.6	Colorless		$b=a$ $c=c$	1.630	1.637	1.647	.011	.1111	$\parallel c$	+	2V=36°	+	Granular, also tabular; rare	Barite, $BaSO_4$.
1.64–.02	V	110 (p)	0–6.5	3–3.4	Blue	a, yellowish; b, violet blue; c, dark blue.	$b=b$ $c:c=+5°$	1.621	1.638	1.639	.018	.001	$\parallel c$	+	2V=42–50°	–	Soda-hornblende	Glaucophane, $NaAlSi_2O_6(FeMg)SiO_3$.
1.65–.02	V	(110 (p)–101 (less p)–010 (less p).	5.5	3–3.47	Green and brown (basaltic)	a, yellow or brown; b, green or brown, c, green or yellow.	$b=b$ $c:c=+15°–25°$	[1] 1.629 [2] 1.677	[1] 1.642 [2] 1.695	[1] 1.653 [2] 1.708	[1] .024 [2] .031	[1] .011 [2] .013	$\parallel c$	+	2V=84°	–	Characteristic color, pleochroism, extinction angle, and elongation; prismatic, widely distributed in rocks and soils; common amphibole.	Hornblende, a complex silicate of Ca, Mg, Fe, Al, Na.
1.65+.03	V	110	6–7	3.1–3.2	Colorless, yellowish		$b=b$ $c:c=+25°$	1.651	1.660	1.677	.026	.008	$\parallel c$	+	2V=54°–60°	+	Prismatic	Spodumene, $LiAl(SiO_3)_2$.
1.66+.01	IV	110	5–5.5	3.1–3.3	Yellowish, brownish, green	a, pale yellow; b, brownish yellow; c, green.	$b=a$ $c=b$	1.656	1.659	1.665	.009	.007	$\parallel c$	+	2E=135°	+	Fibrous and prismatic	Enstatite $(MgFe)SiO_3$.
1.66+.02	IV	010 (p)	6–7	3.17–3.24	Colorless, brownish greenish		$b=a$ $c=c$	1.660	1.661	1.682	.022	.021	$\parallel c$	+	2V=31–42°	+	Prismatic; at times fibrous	Sillimanite, Al_2SiO_5.
1.66+.04	IV	010	6.5–7	3.2–3.31	Green, brownish, colorless	Weak	$a=a$ $b=c$	1.654	1.670	1.689	.035	.019			2V=88°	+	In grains	Olivine $(MgFe)_2SiO_4$.
1.67–.15	IV	110	3.5–4	3.6–3.8	Colorless		$c=a$ $a=c$	1.518	1.564	1.665	.147	.001	$\parallel c$	–	2E=10°	–	Rare	Strontianite, $SrCO_3$.
67–.04	V		5–5.5	2.9–3	do		$b=b$ $c:c=1–1°$	1.626	1.653	1.670	.044	.017	$\parallel c$	+	2V=78°	–	do	Datolite, $Ca(BOH)SiO_4$.
67+.03	V	110	5–6	3.1–3.4	Colorless to green		$b=b$ $c:c=38–45°$	1.673	1.680	1.702	.030	.021	$\parallel c$	±	2V=60°	+	Granular; at times fibrous	Diopside, $Ca(MgFe)(SiO_3)_2$.
.68–.15	IV	010	3–3.75	4.29–4.35	Colorless		$a=c$ $c=a$	1.629	1.676	1.677	.138	.001	$\parallel c$	–	2E=20°	–	Rare	Witherite, $BaCo_3$.
1.68+.01	IV	110	5.5	3.2	Yellowish, brownish, greenish												Orthorhombic pyroxene intermediate in composition between enstatite and hypersthene. (Compare these two minerals.)	Bronzite $(MgFe)SiO_3$.
1.68+0.02	V	110–100–010	4	3.2–3.35	Greenish to brownish												Compare diopside; intermediate in composition between diopside and augite; not very different from diopside; distinguished chemically from diopside.	Hallage.
1.69–0.16	IV	010–110	3.5–4	2.9–3	Colorless		$b=c$ $c=a$	1.519	1.682	1.686	.156	.004	$\parallel c$	–	2E=31°	–	Occurs in rod-like aggregates; sometimes fibrous or acicular.	Aragonite, $CaCO_3$.
1.68–0.01	VI	010	6.5–7	3.3	Brownish gray to bluish gray	a and c, colorless; b, violet to colorless.		1.672	1.678	1.681	.009	.003			2V=72°	–	Rare; crystals wedge-shaped	Axinite, $H(CaFeMn)_3Al_2BSi_4O_{16}$.
1.70–0.01	IV	010	5–6	3.3–3.5	Dark brown	a, red; b, reddish yellow; c, green.	$a=a$ $c=c$	1.692	1.702	1.705	.013	.003	$\parallel c$	+	2V=90–70°	–	Prismatic	Hypersthene $(Mg,Fe)SiO_3$.
1.70–0.00	IV	010 (p)	5–6.5	3.25–3.37	Gray, yellowish		$a=c$ $c=a$	1.697	1.699	1.702	.005	.003	$\parallel c$	–	2V=51°	+		Zoisite, $HCa_2Al_3Si_3O_{13}$
1.71–0.02	V	110	5.5–6	3.11–3.46	Black, dark blue	a, green blue; b, lavender blue; c, greenish yellow.	$b=b$ $c:a=-12–15°$	1.687	1.707	1.708	.021	.001	$\parallel c$	–	2V large	–	Alkali amphibole; prismatic; rare	Arfvedsonite, Silicate of Fe, Na, Al, Ca, Mg.
1.70+0.02	V	110	5–6	3.2–3.6	Green	a, weak greenish yellow; b, brownish; c, greenish.	$b=b$ $c:c=+38–54°$	1.698	1.704	1.723	.025	.016	$\parallel c$	±	2V=61°	+	Prisms, elongated, parallel to c	Augite, complex silicate of Ca, Mg, Fe, Al.
1.73–0.02	VI	100 (p)–110 (less p)	$\parallel c=4–5$. $\perp c=6–7$.	3.56–3.67	Colorless, bluish		a $\perp$ 100. Extinction 30°	1.712	1.720	1.728	.016	.008	$\parallel c$	+	2V=83°	–	Usually in long-bladed crystals and cleavage plates.	Cyanite, Al_2SiO_5.
1.74–0.00	V	001 (p)	6–7	3.3–3.57	Gray to black	a, olive green; b, blue; c, yellowish green.	$b=b$ $c:c=12°–21°$		1.71		.015	.010	$\parallel (101)$	+	2V large	+	Micaceous cleavage; rare	Chloritoid (Ottrelite), $H_2(Fe,Mg)Al_2SiO_7$.
1.74–0.01	IV	010	7–7.5	3.65–3.8	Reddish brown	a, Colorless; b, pale yellow; c, golden yellow	$b=b$ $c=c$	1.736	1.741	1.746	.010	.005	$\parallel c$	+	2V=88°	+	Flat prisms, also cruciform twins	Staurolite, $HFeAl_5Si_2O_{13}$.
1.75–0.04	V	001 (p)–100 (less p)	6–7	3.3–3.5	Green, yellowish, colorless	a, yellow or green; b, blue to green or yellow; c, yellow to green.	$b=b$ $c:a=-3$	1.714	1.741	1.746	.032	.005	$\parallel b$	±	2V=74–88°	–	In grains, also prismatic and fibrous; common in all soils.	Epidote, $Ca_2(Al,Fe)_3$ $(AlOH)\,(SiO_4)_3$.
1.80+0.04	V	001–101	5.5	4.0–5.3	Brownish to reddish	Colorless to yellowish	$b=b$ $c:c=+4°$	1.796	1.797	1.841	.045	.044	$\parallel c$	+	2E=77°	+	In grains; distinguished by the index; rare	Monazite, $(CeLaDi)PO_4$.
1.81–0.05	V	110	6–6.5	3.44–3.46	Dark brown	a, brown; b, light brown; c, greenish yellow.	$b=b$	1.763	1.791	1.813	.050	.014	$\parallel c$	–	2V=42°	–	Sometimes only zonally enveloping augite; aegirite and acmite are distinguished by their colors.	Acmite, $NaFe(SiO_3)_2$, aegirine.
1.82–0.05					Greenish black	a, dark green; b, olive green; c, yellowish green.	$c:c=3–6°$	1.771	1.810	1.824	.053	.014						
1.80+0.11	V	110	5–5.5	3.4–3.6	Brown, yellow, green, reddish		$b=b$ $c:c=+61°$	1.883	1.891	2.000	.121	.015	$\parallel c$		2V=27°	+	In flat, wedge-shaped crystals; also in grains	Titanite, $CaTiSiO_5$.
2.5	IV (?)	001	5–5.5	3.6–4	Red, brown; at times yellowish	a, yellow; b, brownish yellow; c, orange yellow.	$b=a$ $c=c$		2.5		.048		$\parallel c$	+	2V=large		An alteration product of iron minerals, the common pigment in soils, generally opaque.	Limonite, $Fe_2(OH)_6O_3$

[1] Common.

[2] Basaltic.

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